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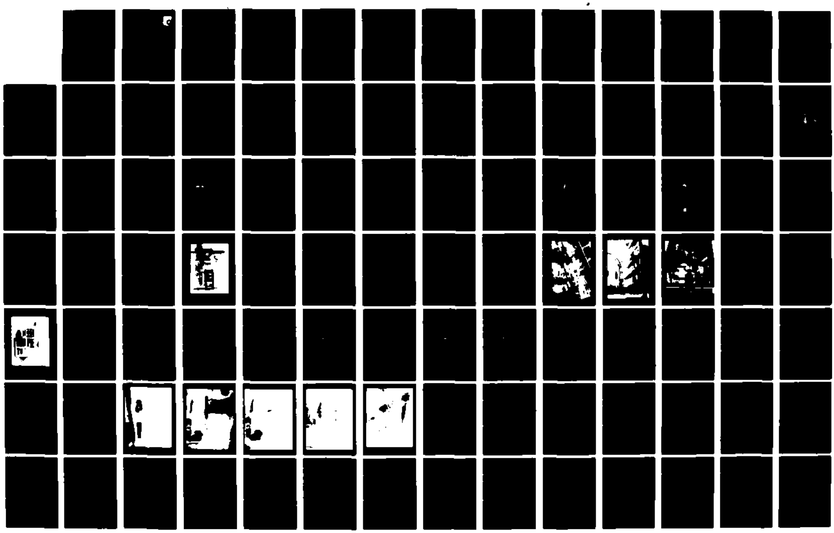

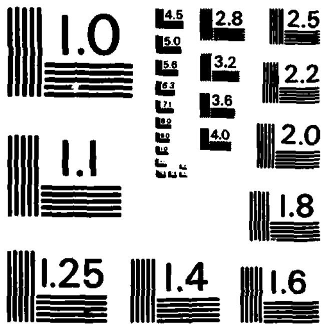

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AFWAL-TR-82-2067

FUEL/ENGINE/AIRFRAME TRADE-OFF STUDY

OPERATIONAL EFFECTS OF INCREASED FREEZE POINT FUELS

Boeing Military Airplane Company
Advanced Airplane Branch
P.O. Box 3707, Seattle, Washington 98124

August 1982

Final Report for Period 2 March 1981 - 12 April 1982

Approved for Public Release, Distribution Unlimited

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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This technical report has been reviewed and is approved for publication.

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This study of extreme low temperature C-141, KC-135, and B-52 operational missions indicates that the -58°C freeze point specification for JP-4 fuel is ultra conservative. The study suggests that the freeze point could be increased by at least 12°C with no effect on in-flight performance and that there is a good possibility that commercial, Jet A fuel (-40°C freeze point) would be acceptable for these aircraft. A method of identifying realistic extreme low temperature, in-flight exposure and airplane fuel system response was developed. The ground environmental extremes were not studied and could impact the conclusions.

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PREFACE

This final report is submitted by the McDonnell-Douglas Aircraft Company, Long Beach, California. The work was conducted under Contract F33615-78-C-2001. Dates of research were March 2, 1981 through April 12, 1982. Program sponsorship and guidance were provided by the Aero Propulsion Laboratory (AFWAL/POSF), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 304805 and Work Unit 30480589. Charles Delaney was the government project engineer.

Test fuel characterization was provided by AFWAL/POSF. NASA Lewis Research Center provided the LFP-14 test fuel used in this program. The mission data for the B-52 and the KC-135 was obtained from the Operational Analysis Group of the Boeing Military Airplane Company (BMAC), Wichita, Kansas. C-141 mission data were obtained from Lt. Col. G. F. Sacre, Headquarters MAC, Scott AFB, Illinois. The cooperation of these individuals and organizations is appreciated.

The key McDonnell-Douglas contributor to this program was A. T. Peacock, Program Manager. Key Boeing contributors to this program under subcontract AS20803-C were: F. F. Tolle, technical program manager; H. M. Fuglvog, test engineer; L. A. Massmann and P. M. McConnell, flight data and thermal analysis; and G. N. Peterson, principal investigator.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A = fuel tank area

C_1 = empirical constant

C_2 = empirical constant

c_p = specific heat, constant pressure

c_v = specific heat, constant volume

G_r = Grashof number

h_i = internal convective heat transfer coefficient

h_o = external convective heat transfer coefficient

h_{SL} = heat transfer coefficient, solid liquid interface

k = thermal conductivity, liquid fuel

k_s = thermal conductivity, solid fuel

L_c = characteristic length

L_h = horizontal length

L_v = vertical height

L_f = latent heat of solidification

m_i = mass of i^{th} layer

m_t = total mass

M_∞ = free stream Mach number

N = number of subdivisions

P_r = Prandtl number

r = recovery factor

T_a = ambient temperature

T_b = bulk temperature

T_f = fuel temperature

T_r = recovery temperature

T_{pp} = pour point temperature

T_∞ = free stream temperature

ΔX = thickness of incremental fuel layer

α = thermal diffusivity

γ = c_p/c_v

ε = coverage distance to solid-liquid interface

τ = time

ρ = density of liquid fuel

ρ_s = density of solid fuel

1.0 SUMMARY

The objective of this study was to determine in-flight operational effects of using higher freeze point fuels in military airplanes. The principal measure of operational effect was fuel not available to the engines because of frozen fuel in the tanks; this trapped fuel is referred to as "hold-up" in the succeeding discussion. The three airplanes selected for the study were the C-141, KC-135, and B-52. The study was divided into the following tasks:

Task I - Route Structure Model Development for each Airplane with Emphasis on Arctic and Long High Altitude Flights

Task II - Fuel System Study to Determine the Most Critical Fuel Tanks for Susceptibility of Cold Fuel Effects

Task III - Thermal Exposure Data Base (Identify 15 Worst Case Days)

Task IV - Fuel Temperature Calculations (10 most northernly tracks for each airplane)

Task V - Estimation of Loss of Mission Available Fuel due to Fuel Freezing

Task VI - Confirmation of Analytical Studies using Cold Fuel Wing Tank Simulator

The principal conclusion is:

- The $-58^{o}C$ freeze point specification for military aircraft fuel, JP4, is too conservative. The results indicate that the freeze point could be increased by at least $12^{o}C$ with no effect on operational performance. The study suggests that there is a possibility that commercial, Jet A fuel ($-40^{o}C$ freeze point) might be an acceptable fuel for the study aircraft. It is important to note that extremes of low temperature ground environment and their effects on fuel systems were not studied; this environment could be more limiting than the flight environment.

Other significant results are summarized as follows:

- A realistic method of studying enroute temperatures and resultant fuel tank temperature profiles during an airplane mission has been established.

- Verification of predicted tank temperature profiles was achieved using cold fuel tests in a 182.4 liter wing tank simulator. Predicted temperatures were within $\pm 2^{0}C$ of those measured when the tank was full of liquid. However, when analytic predictions of the percent hold-up exceeded 10%, the experimental results showed the actual hold-up to be significantly less. Thus the analytic predictions are conservative.

- The heat transfer process (during cooling) consists of a convection zone in the upper portion of the tank and a conduction zone at the bottom. During heating the process is reversed with conduction occurring at the top and convection at the bottom. Convection is the dominant mode of heat transfer in both cases. The presence of a small ullage volume (approximately 1 cm in thickness) in the critical fuel tanks significantly reduces the convection heat transfer.

Comments and recommendations include:

- Hold-up was always measured by the difference between the fuel loaded into the simulator and the fuel which could be drained from it. With liquid fuel in the tank, visual evidence of hold-up was not obtainable; neither were observations of the formation and thawing of frozen fuel during cooling and warming periods because of the "waxy" dark yellow color of the fuel at low temperatures. Efforts to improve visibility by changing tank lighting and attempts to remove water by bubbling dry nitrogen through the fuel prior to loading the simulator were unsuccessful.

- Solid-liquid (slurry) formations were observed to flow through the drain line (transparent tubing) during tank emptying preceding hold-up measurements. This observation suggests that the fuel slurry would not impede the flow of the major portion of the liquid from the tank.

- Approximately 3% hold-up is considered a practical limit which could be tolerated in a fuel tank, since 97% of the fuel would still be usable and blockage of flow passages would be a remote possibility with such a small solid fraction. With higher amounts of hold-up present, there is a risk of flapper check valves in the stringers becoming bridged shut, thus trapping liquid fuel between stringers.

Some gaps remain in the study of fuel at low temperatures. Recommended future work includes

- in-flight measurements for verification of analysis and experimental simulation
- extension of the analysis to include wall curvature (cylindrical tanks)
- improvement in the hold-up prediction in the presence of frozen fuel
- a study of typical ground temperature effects.

2.0 INTRODUCTION

The very low freeze point requirement for military jet fuel (-58^{o}C) is a factor which can restrict production, particularly at refineries with limited crude availability. It has been estimated that a 3^{o}C relaxation in freeze point limit would increase jet fuel availability by about 9% (Ref. 1). Although there are no operational performance data with higher freeze point fuels in U.S. military aircraft, there is a growing body of experimental simulation data and analyses to support the argument that the freeze point specification established by MIL-STD-210B guidelines is too conservative. The objective of this study was to gain further understanding of the operational effects of using higher freeze point fuels in typical military aircraft.

2.1 TASKS

This study was subdivided into six tasks, details of which can be found in the indicated sections of this report:

Task I	Selection of operational routes for the C-141, B-52 and KC-135 airplanes with emphasis on Arctic and long/high altitude flights (Section 3.1 and Appendix A)
Task II	Analysis of fuel systems with respect to low temperature exposure (Section 3.2 and Appendix B)
Task III	Determination of thermal exposure of fuel system by identification of 15 worst case days (Section 3.3 and Appendix C)
Task IV	Calculation of fuel temperature profiles during typical "worst case" mission for 10 northernmost tracks for each airplane (Section 3.4 and Appendix D)
Task V	Development of procedures to estimate percent hold-up in fuel tanks for selected fuels (Section 3.5)
Task VI	Verification of analytical studies by experiment (Section 4.0)

2.2 APPROACH

Three airplanes were to be selected for this study from different misson classes and their operating scenarios determined for critical peacetime or wartime missions. Each airplane was to use a major fraction of the annual USAF fuel burn and special emphasis was to be placed on long endurance, high altitude flights which penetrated Arctic regions. The B-52 was selected as typical of the bomber class, the KC-135 of the refueler class, and the C-141 of the transport class.

Tasks I - VI were performed sequentially since each step depended on results from the preceding ones. The approach to task accomplishment consisted of the following steps:

Calculation of Thermal Exposure

- identification of routes, in particular the ten northernmost routes along which each aircraft could expect to fly

- identification of the most critical task from a low temperature standpoint

- generation of fuel tank wetted area and fuel quantity for the critical tank as a function of time of flight for each aircraft

- development of a thermal exposure data base, and definition of ambient temperature versus time of flight along each route,

- calculation of the fuel thermal profile development (fuel temperature versus fuel tank height) in the critical tank as a result of the time varying thermal environment

- calculation of the amount of fuel expected to be frozen at different times during the worst case missions

Experimental Verification

- measurement of the fuel freezing characteristics of each of the selected test fuels

- simulation of route temperatures in the cold fuel simulator tank to verify the predictions of thermal profile development computer program and to evaluate fuel freezing (hold-up) predictions

Data generated from the above steps were required for evaluation of the effects of fuel freeze point on flight operations.

3.0 THERMAL EXPOSURE CALCULATIONS

Development of an analytical model for predicting fuel temperature profiles as a function of mission time was required to achieve the objectives of this program. Input data included specific mission tracks, altitude, air speed, ambient in route temperatures, and information regarding the specific fuel system, e.g., the tank geometry and fuel consumption, and fuel management procedures used by the flight crews.

3.1 ROUTE STRUCTURE - TASK I

Operational routes for the B-52, KC-135 and C-141 were obtained for the selected aircraft. The mission chosen for the KC-135 was that of refueling the B-52 airplanes. Accordingly, the KC-135 ground tracks coincide with the initial portions of the B-52 tracks; however, the KC-135s turn around after refueling (usually just prior to B-52 penetration) and return to the takeoff base. For each of the study aircraft, ten routes were selected which emphasized Arctic and long endurance/high altitude flights. Mission tracks were converted into longitude, latitude, and altitude data (Appendix A). The air speed and fuel consumption were deduced from flight operating manuals.

The ten selected mission tracks for the B-52 are shown plotted on a polar projection of the world in Figure 3-1. The B-52's are accompanied by a KC-135 refueler to the refueling point, where the KC-135 reverses course and returns to the point of origin. It was established that other KC-135 missions were no more severe than those shown in Figure 3-1. The B-52/KC-135 tracks are representative of wartime missions and the probability of flying these or similar tracks during wartime is estimated to be 80%. B-52/KC-135 peacetime tracks were determined to take place in warmer climates and therefore were not considered in this study.

The C-141 tracks examined (Fig. 3-2) are expected to be flown in peacetime or wartime. The probability of flying the selected routes was estimated to be 2%, based on a sample of C-141 fleet experience in which the given routes were flown 142 times out of 6522 sorties.

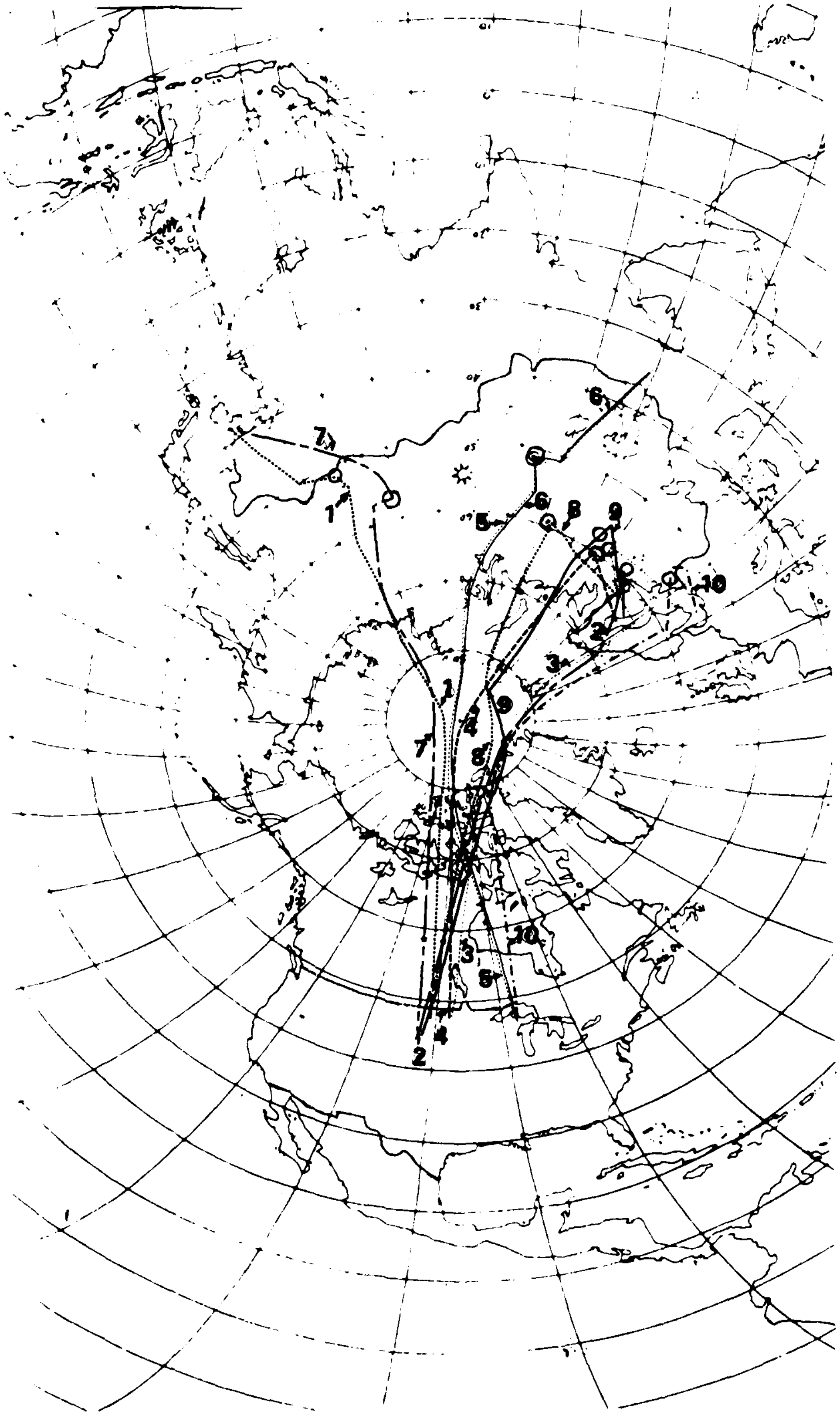


Figure 3-1. B-52/KC135 Trajectories

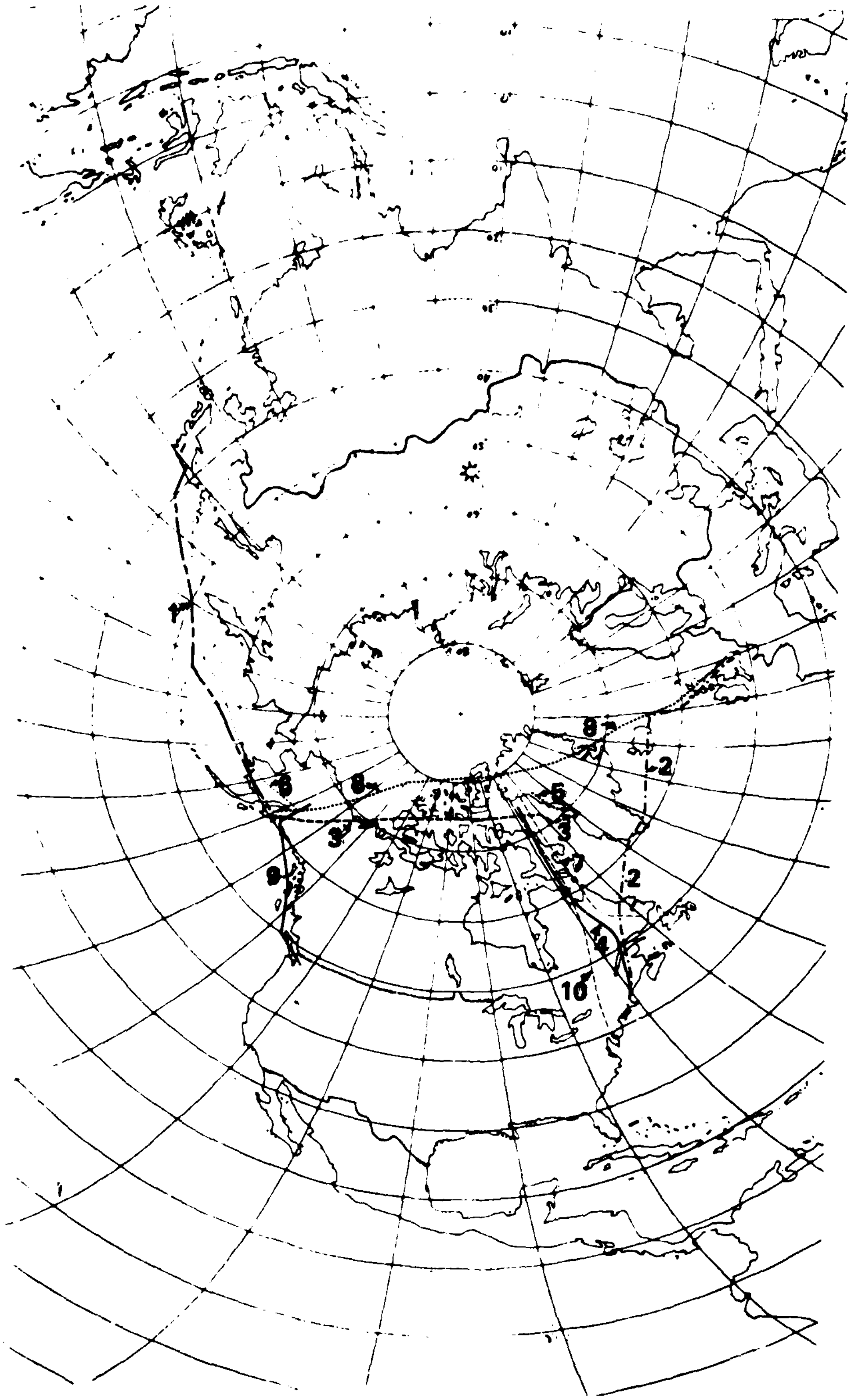


Figure 3-2. C-141 Trajectories

3.2 FUEL SYSTEM STUDY - TASK II

The low temperature critical fuel tank for each study aircraft is the one which contains fuel longest and exposes its contents to the low temperature environment. This tank was the one with the largest percent fuel wetted area per fuel volume, generally a wing tank, and usually the wing tank from which fuel is used last. Fuel tank locations of the three study aircraft are shown in Figures 3-3 through 3-5.

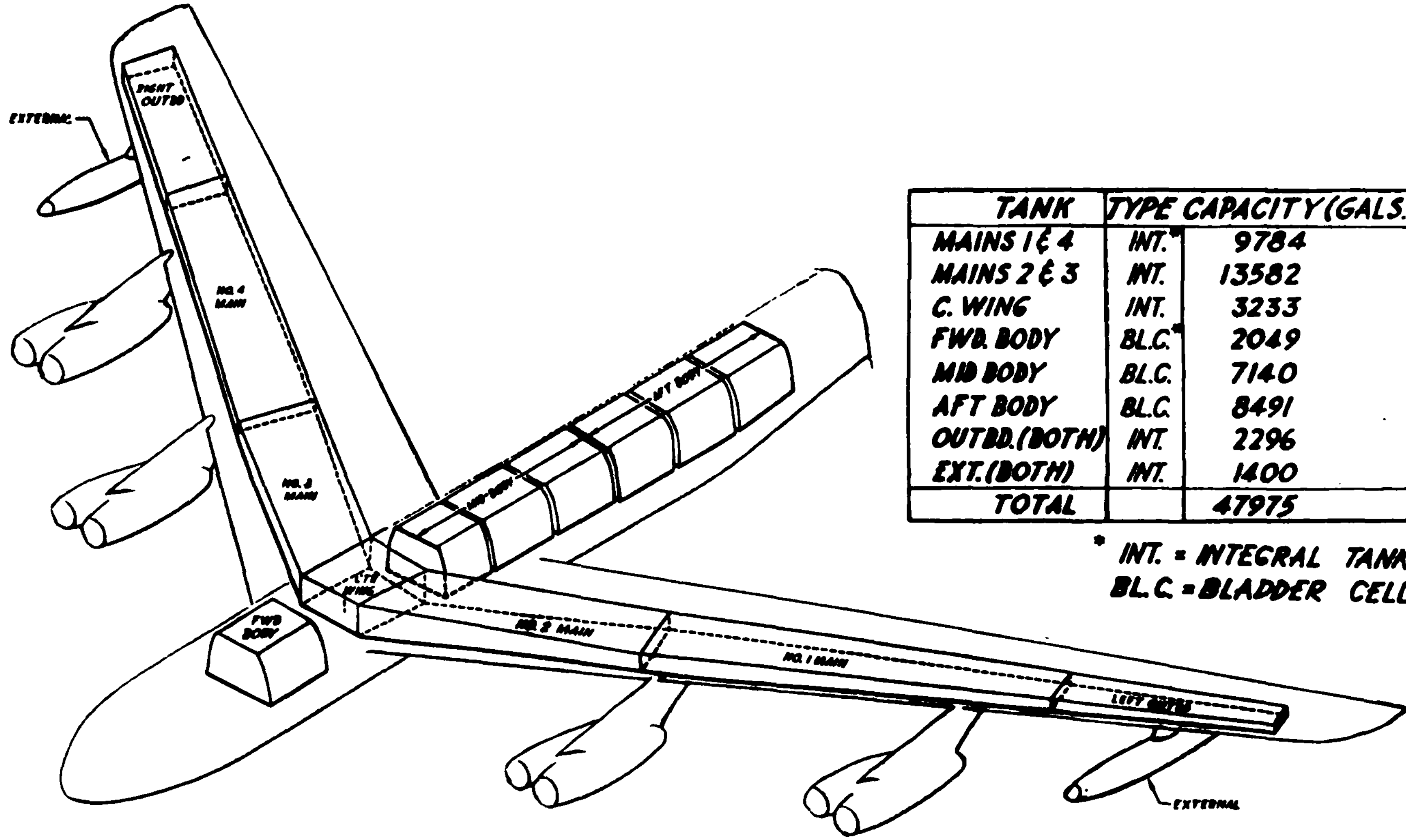
The fuel utilization schedule from the airplane flight manual together with airplane performance data were used to determine fuel quantity in each tank versus route position and time. Fuel usage sequences are given in Appendix B, Tables B-1 through B-3, where it can be seen that usage of outboard wing fuel is deferred until late in a flight; this usage is dictated by structural design considerations so as to reduce wing bending moments. Alteration of the sequence of fuel usage on a routine basis could therefore be expected to reduce the airplane's structural life; however, it might be expedient to use such a procedure when facing extreme low ambient temperature flight conditions.

The geometry assessment involved inserting wing tank structural layouts and airfoil shapes into the Boeing TEM256 computer program, which gives fuel tank wetted area as a function of fuel volume. The following geometrical factors are entered into the program:

- o tank end locations
- o airfoil cross sectional dimensions at the tank ends (all critical tanks had linearly varying airfoil sections between tank ends)
- o dry bays or significant internal structure needed to be deducted from exposed area or tank volume
- o wing orientation during cruise, i.e., dihedral, incidence, twist and deflection

Calculated fuel tank ullage depth, fuel volume and wetted tank area data are given in Appendix B, Tables B-4 through B-7. The low temperature critical integral wing tanks for each airplane were determined to be:

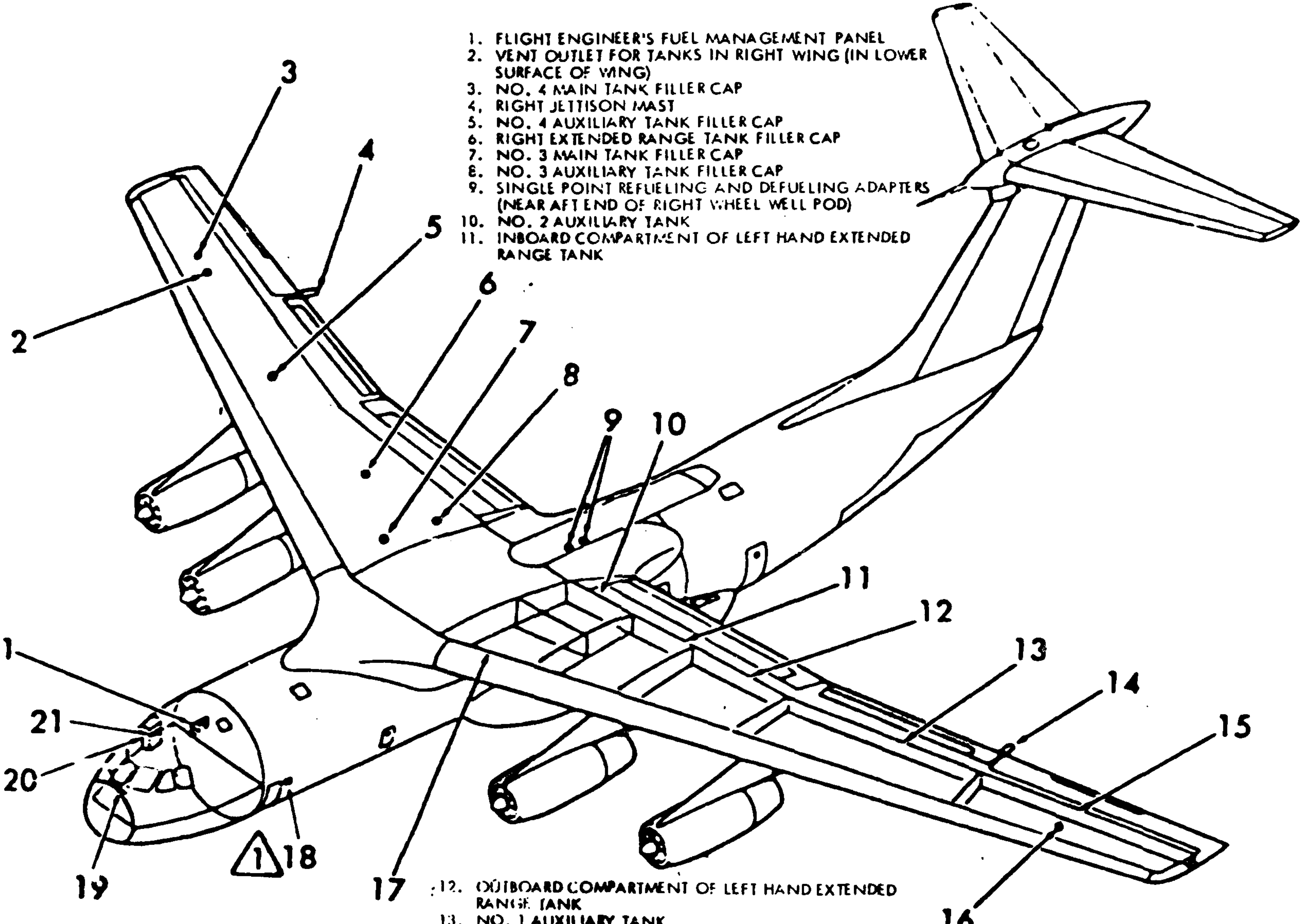
- o B-52 -- the outboard wing tanks
- o C-141 -- the No. 1 and 4 main tanks
- o KC-135 -- the No. 1 and 4 reserve tanks



TANK	TYPE	CAPACITY (GALS.)
MAINS 1 & 4	INT.*	9784
MAINS 2 & 3	INT.	13582
C. WING	INT.	3233
FWD. BODY	BL.C.*	2049
MID BODY	BL.C.	7140
AFT BODY	BL.C.	8491
OUTBD. (BOTH)	INT.	2296
EXT. (BOTH)	INT.	1400
TOTAL		47975

* INT. = INTEGRAL TANK
BL.C. = BLADDER CELL

Figure 3-3. B-52 Fuel Tank Locations



1. FLIGHT ENGINEER'S FUEL MANAGEMENT PANEL
2. VENT OUTLET FOR TANKS IN RIGHT WING (IN LOWER SURFACE OF WING)
3. NO. 4 MAIN TANK FILLER CAP
4. RIGHT JETTISON MAST
5. NO. 4 AUXILIARY TANK FILLER CAP
6. RIGHT EXTENDED RANGE TANK FILLER CAP
7. NO. 3 MAIN TANK FILLER CAP
8. NO. 3 AUXILIARY TANK FILLER CAP
9. SINGLE POINT REFUELING AND DEFUELING ADAPTERS (NEAR AFT END OF RIGHT WHEEL WELL POD)
10. NO. 2 AUXILIARY TANK
11. INBOARD COMPARTMENT OF LEFT HAND EXTENDED RANGE TANK
12. OUTBOARD COMPARTMENT OF LEFT HAND EXTENDED RANGE TANK
13. NO. 1 AUXILIARY TANK
14. LEFT JETTISON TANK
15. NO. 1 MAIN TANK
16. VENT OUTLET FOR TANKS IN LEFT WING (IN LOWER SURFACE OF WING)
17. NO. 2 MAIN TANK
18. APU FIRE CONTROL HANDLE (MANUAL FUEL SHUTOFF VALVE)
19. ENGINE MANUAL FIRE SHUTOFF VALVE CONTROL HANDLES
20. FLIGHT ENGINEER'S CONTROL PANEL
21. APU CONTROL PANEL

Figure 3-4. C-141 Fuel Tank Locations

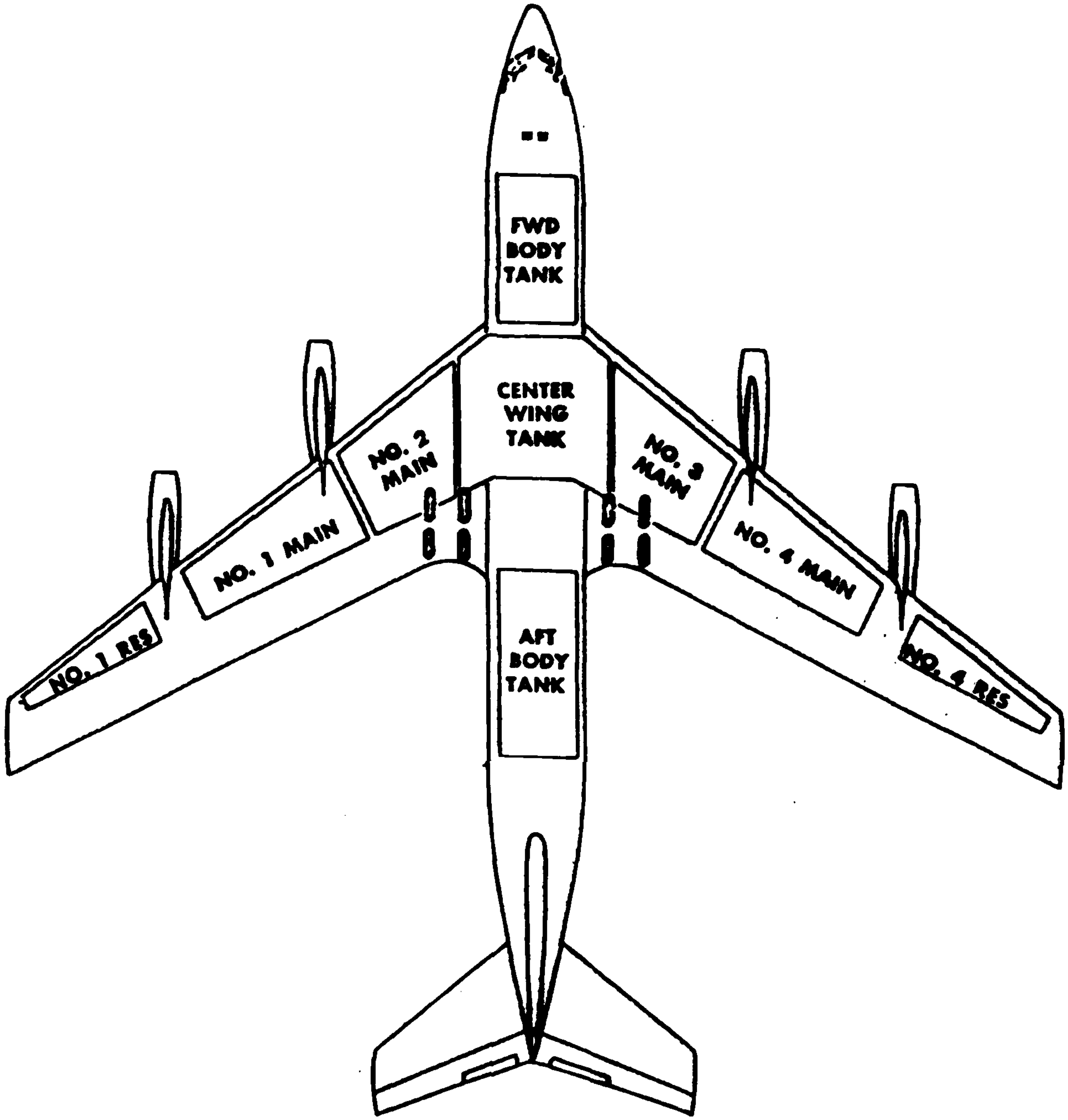


Figure 3-5. KC-135 Fuel Tank Locations

3.3 AMBIENT TEMPERATURES - TASK III

The objective of Task III was to develop statistical information relative to thermal exposures along the routes selected in Task I. The basis for these calculations is a library of magnetic tapes which were acquired from the National Center for Atmospheric Research (NCAR). The tapes contain twice-daily records of temperature and wind at 1977 grid points covering most of the Northern Hemisphere (Fig. 3-6). Data are provided for seven pressure altitudes:

100 mbar	(approximately 53,000 ft)
150 mbar	(approximately 45,000 ft)
200 mbar	(approximately 40,000 ft)
250 mbar	(approximately 34,000 ft)
300 mbar	(approximately 30,000 ft)
500 mbar	(approximately 18,000 ft)
700 mbar	(approximately 10,000 ft)

Figures 3-1 and 3-2 show that the tracks of the B-52 and C-141 cover significantly different areas of the northern hemisphere. The fifteen coldest days (on a time weighed basis) for each track were extracted from the 10 year period of NCAR meteorological data. Only the winter months (15 December through 14 March, 1966 through 1975) data were searched because the routes are all restricted to northern regions. This data base contains 7300 samples and is considered adequate to define the worst case cold days as reported in Appendix C, Figures C-1 through C-30. The meteorological data were extracted from NCAR records for the individual aircraft tracks by specifying the longitudes, latitudes, and pressure level (altitude) that define the aircraft tracks; the thermal exposure of the aircraft at points between the established grid (Fig. 3-6) was determined by interpolation. Once the above data were extracted, they were stored on a separate tape for future runs with the same aircraft.

From the 15 coldest days the single worst case cold day, as defined by the minimum average temperatures, was determined for each of the mission tracks. This worst case single day's ambient temperature and recovery temperature are plotted versus time for each of the aircraft tracks in Appendix C, Figures C-31 through C-60. The recovery temperature is defined as

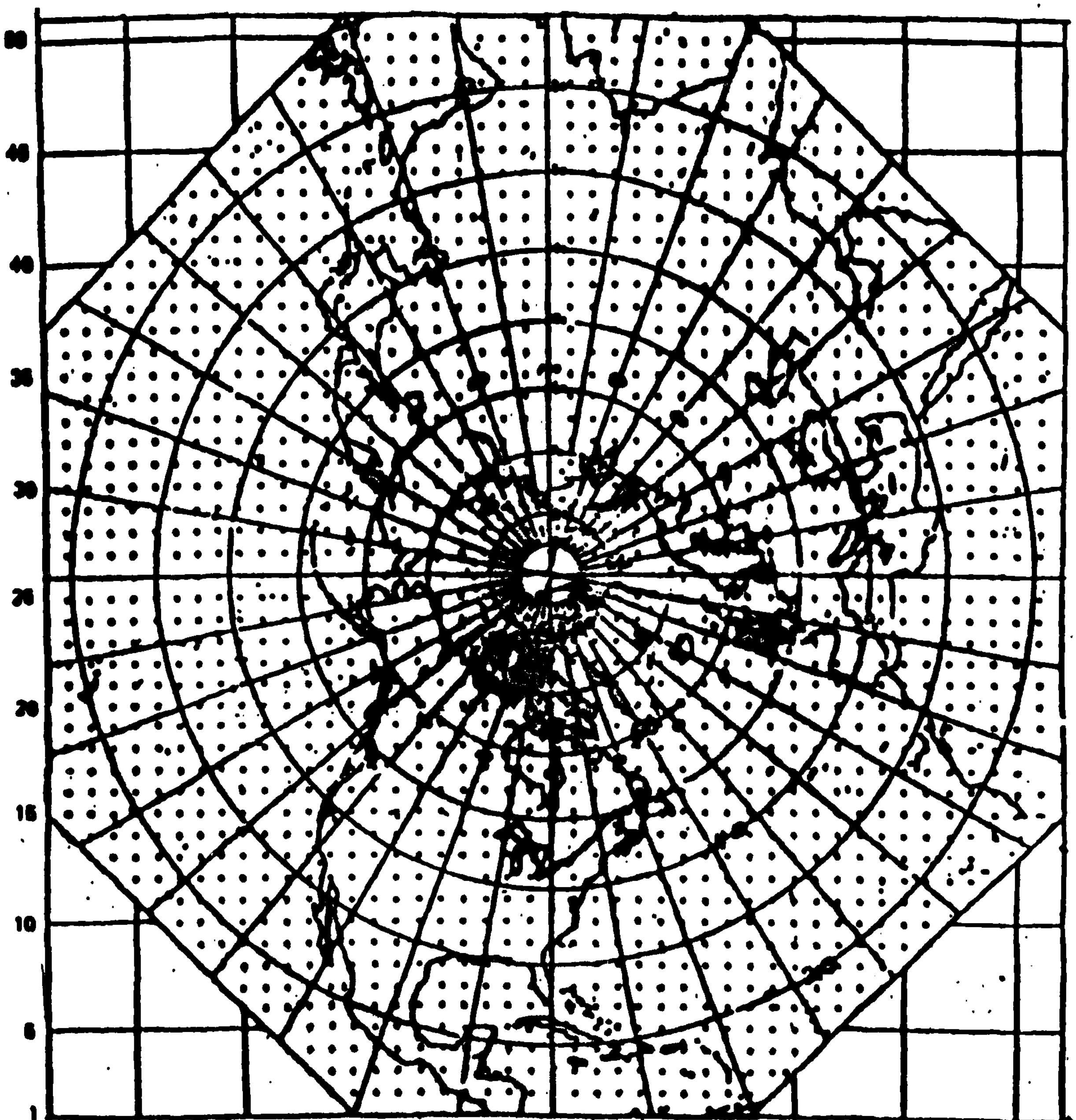


Figure 3.6 NCAR Meteorological Grid

$$T_r = T_\infty[1 + r(\frac{\gamma-1}{2})M_\infty^2] \quad (1)$$

where,

T_∞ = free stream temperature

M_∞ = free stream Mach number

r = recovery factor ($\approx$ 0.9)

γ = c_p/c_v (1.4 air)

3.4 FUEL TEMPERATURE CALCULATION - TASK IV

In the development of the analytical method to calculate fuel temperatures it is necessary to account for the following factors which contribute to the heat transfer:

- o initial fuel temperature resulting from pre-flight ambient exposure
- o periodic transitions from cooling to heating to cooling of the fuel tanks caused by flying into and out of warmer air masses
- o changing wetted area of the fuel tank as fuel is consumed from it
- o influence of increasing fuel ullage on heat transfer

A flow diagram of the computational procedure is shown in Figure 3-7.

3.4.1 General Description of Heat Transfer Model

The problem of calculating fuel temperatures was reduced to a one-dimensional transient heat transfer problem $T=T(x,\tau)$, i.e., variation of temperature in the lateral and fore-and-aft directions was considered negligible compared to top and bottom variations. This assumption is based on order of magnitude arguments which consider tank depth to tank lateral dimensional ratios. Because tank depth varies in the spanwise direction, the region modeled was chosen to be the inboard portion of the fuel tank. The major low temperature effects were anticipated to occur in this location since the fuel in that zone of the tank is usually used last. The analysis includes both heating and cooling phenomena in a full (100% liquid fuel) tank, or a partially full (liquid and ullage) tank, but cannot at this time be used when significant amounts of frozen fuel are present.

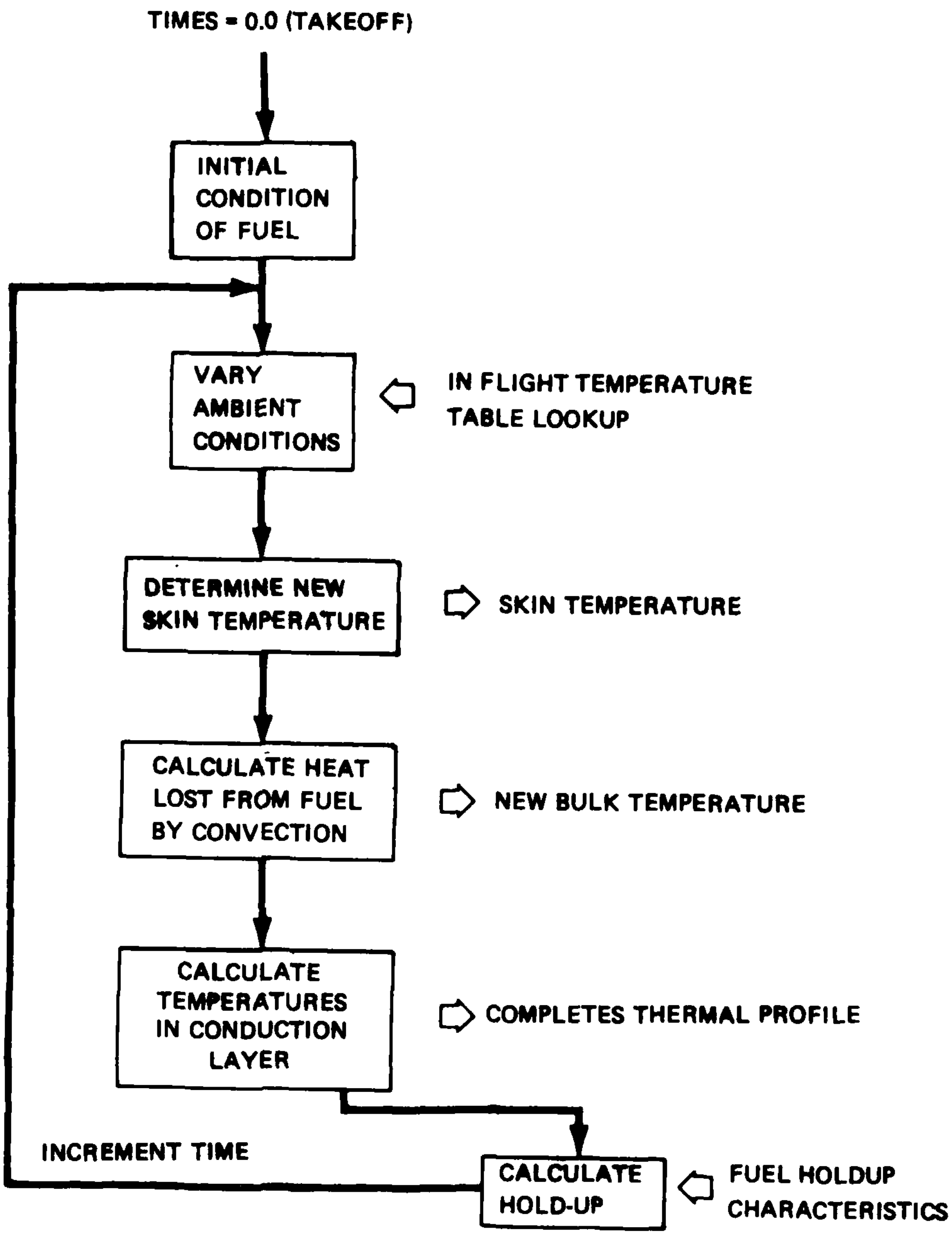


Figure 3-7. Flow Diagram for the Thermal Analysis Computer Program

The recovery temperature, T_r, was assumed to be constant over the tank surface. This assumption is reasonable since the turbulent flow recovery factor, r, is approximately equal to the cube root of the Prandtl number and has little chordwise or spanwise variation over the wing surface.

Some of the heat transfer phenomena which are modeled are described with reference to Figure 3-8; heat transfer processes depend on the relative magnitudes of T_s and T_f, where T_s is the skin temperature, and T_f is a characteristic fuel temperature. Since the processes are time dependent, both initial and boundary conditions are required in order to obtain a solution.

In a cooling situation ($T_s < T_f$), denser layers of fuel at the top of the tank will tend to settle, establishing a free convective zone in the upper portion of the tank. The cold layer in the bottom of the tank tends to be stagnant, and too dense to be penetrated by the low velocity fuel descending from the top of the tank. Hence heat transfer from the bottom skin to the fuel is primarily by conduction. At the beginning of the cooling process when the tank is full, the majority of fuel is involved in the convection process; because of convectively driven mixing, this zone is characterized by a nearly constant (bulk) temperature. Over time, as the temperature of the fuel drops and approaches that of the skin, the driving force for convection is reduced; the convection zone decreases in depth while the conduction zone grows.

During heating of the fuel ($T_s > T_f$), the heat transfer processes described in the preceding paragraph invert, with a convection zone at the bottom and a conduction zone at the top of the tank.

As fuel is consumed from the tank and an airspace develops at the top of the tank, the computer program accounts for the reduction in heat transfer at the upper skin. In the cooling case, ($T_s < T_f$), convective heat transfer through the air at the top of the tank is much less than when the upper skin is wetted with fuel; since convection is the dominant cooling mode in a fuel tank, the overall heat transfer from the tank is considerably less once a ullage develops.

T_∞ = AMBIENT TEMPERATURE
T_r = RECOVERY TEMPERATURE
T_S = SKIN TEMPERATURE
T_b = BULK FUEL TEMPERATURE

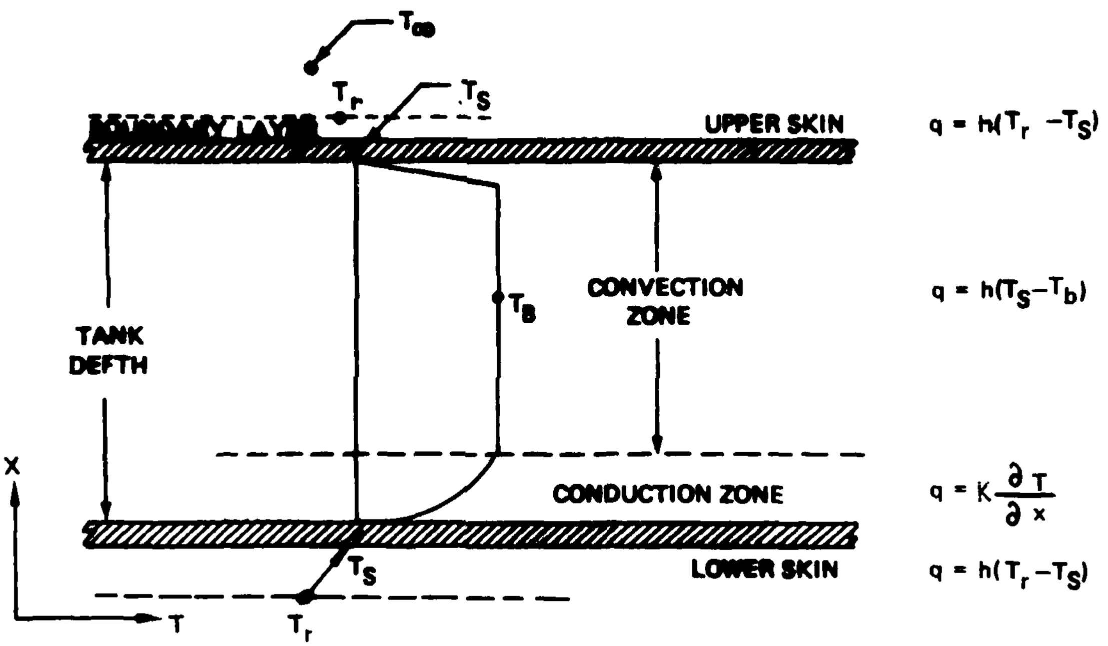


Figure 3–8. Schematic of Tank Temperature Profile During Cooling, $T_s < T_b$

3.4.1.1 Analytic Procedures for Calculating Fuel Temperature

A computer program has been developed to solve the transient heat transfer problem outlined above. The computer program evaluates internal conditions in the tank by:

- reference to the Grashof number in the convective zone
- solving the unsteady thermal diffusion equation in the conduction zone
- matching temperatures at the convective - conduction zone interface

When the temperature differences between the tank skin and the bulk fuel are large, the free convection flows are likely to be turbulent. For smaller differences, the flow tends to be laminar. The criterion used is the Grashof number (Gr). Accordingly, the free convective heat transfer correlations used in the thermal analysis are the form:

Laminar: $h = C_1(Gr \cdot Pr)^{1/4}\, k/L_c$ for Gr: 10^5 to 2×10^7 (2)

Turbulent: $h = C_2(Gr \cdot Pr)^{1/3}\, k/L_c$ for Gr: 2×10^7 to 3×10^{10} (3)

Values of C_1 and C_2 used in the above correlations were 0.14 and 0.54 respectively. These constants may in fact be weakly dependent on tank height. Aside from this, the length term in the turbulent correlation (Equation 3) cancels with a like quantity in the Grashof number and heat transfer would be independent of tank height in turbulent free convection. The characteristic length used in the heat transfer correlations, Equations (2) and (3), was defined as

$$L_c = \frac{L_h \cdot L_v}{L_h + L_v} \tag{4}$$

where L_h = maximum horizontal dimension
L_v = height of tank

3.4.1.2 Boundary Conditions

External conditions in the form of route temperature and pressure are introduced by means of a set of boundary conditions which match internal (fuel side) and external (air side) rates of heat transfer. For the cooling case, the boundary conditions have the form:

Bottom Skin $$h_o(T_s-T_r) = K_f \left.\frac{dT}{dx}\right|_{\text{lower skin}} \tag{5}$$

Top Skin $$h_o(T_s-T_r) = \iint_{\text{convection zone}} \rho c_p dT_b dx \tag{6}$$

where,

- h_o = air side convective heat transfer coefficient
- h_i = fuel side convective heat transfer coefficient
- K_f = thermal conductivity of fuel
- T_s = skin temperature
- T_r = recovery temperature, Equation (1)
- T_f = convection zone temperature

Equation (5) is a standard boundary condition; the skin temperature which results is used in Equation (6) to compute the change in convection zone temperature, T_b. In effect, the assumption is made that the upper and lower skin temperatures are equal. The basis for the assumption is the equality of the recovery temperature, T_r, adjoining the skins, and the very low heat flow from the tanks. The skin temperatures which result from the calculation are used to control skin temperatures during simulation of the flight in the laboratory verification tests.

3.4.1.3 Initial Conditions

Initial conditions are introduced in the form of the thermal profile that exists in the tank T = T(x,o) at time of takeoff. This initial profile is generated by using the heat transfer analysis described above, beginning twenty four hours before takeoff according to the procedures described in

Section 3.4.3. The analysis shows that the in-tank fuel temperature profiles at mission start are essentially independent of the temperature at the start of the pre-conditioning period.

3.4.2 Freezing and Melting Analysis

Freezing and melting of aircraft fuel is a complex phenomena since hydrocarbon fuels are mixtures of a large number of molecular compounds. Consequently, fuels do not freeze at a fixed temperature with definable latent heat, as with a pure substance. When a complex fuel mixture is cooled below its freeze point, wax crystals first form near the cooler surfaces and later, as the bulk temperature drops, in suspension in the bulk liquid. As the fuel temperature continues to fall, the crystals gradually increase in size and number. Eventually in the colder regions, the crystals begin to link to form a matrix which is initially slurry-like, with an apparent consistency like applesauce; such petroleum slurries display thixotropic behavior in that when the solid matrix is stirred, the flowability increases. If the temperature is further reduced, the matrix becomes increasingly resistant to flow, and eventually becomes ice-like. Even at this stage, considerable quantities (50% to 70%) of the low freeze point fuel constituents may still be liquid but are trapped within the solid matrix.

Analytical studies of the freezing and thawing process are complicated by the fact that although the behavior of all the individual components of the fuel is known and their solidification properties acting independently are predictable, the solidification properties of the mixture are not predictable because of solubility effects.

Cold fuel simulation tests in which freezing occurs have shown that after draining residual liquid from the tank, frozen fuel was unevenly distributed over top and bottom (cold) tank surfaces. This situation is depicted schematically in Figure 3-8 where the tank skin is exposed to temperatures below the fuel pour point ($T_s < T_{pp}$). If the frozen fuel behaved as a pure substance, the governing conduction equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau}, \qquad 0 \leq x \leq \varepsilon \qquad (7)$$

would apply in the solid region, subject to the following boundary conditions:

$$x=0: \qquad -k_s \frac{\partial T}{\partial x} = h_o \,(T-T_r)$$

$$x=\epsilon \qquad -k_s \frac{\partial T}{\partial x} = \rho_s L_f \frac{d\epsilon}{dt} + h_{SL} \,(T_b-T_{pp})$$

Where, α = $\rho_s c_{ps}/k_s$ thermal diffusivity of frozen fuel

h_{SL} = heat transfer coefficient, solid liquid interface

K_s = thermal conductivity of frozen fuel

ρ_s = density of frozen fuel

L_f = latent heat of solidification

ϵ = average distance to solid-liquid interface

T_{pp} = pour point temperature

$\frac{d\epsilon}{d\tau}$ = volume rate of frozen fuel formation per unit area

Difficulties arise in the application of the above equations to actual aircraft fuel because the usual thermal properties (latent heat of solidification, L_f, specific heat, c_p) are not known. A further problem is that batches of fuel produced to the same fuel specification from different crudes or by different processes may contain quite different molecular blends, and have different thermal property values; within a particular fuel specification, a band of thermal property values is the best that can be expected. Property values during the freezing process are being researched by NASA-Lewis, and when available will make it possible to extend the thermal analysis model to the freezing problem along the lines outlined above.

Experimentally, it will be important to measure the rate of growth of frozen material, $d\epsilon/dt$ to either guide or confirm the analysis. Since the opacity of cold fuel precludes visual observations, one approach which could provide the needed data would be to cool and drain the tank at different times, while repeating the same mission profile, but this would be tedious and expensive. The alternative is to find or develop an instrument which can detect the solid-liquid interface position without draining the task.

In the interim, the computer model will over estimate values of hold-up in cases where more than a few percent holdup are computed. Fortunately, the present prediction technique is conservative, with errors on the safe side.

3.4.3 Profile Calculations

The thermal profile calculations for each mission depend primarily on atmospheric ambient temperature data on the selected day along the mission track. After the worst case days had been identified for analysis of fuel tank hold-up, it was necessary to specify the temperature distribution in the tank at the beginning of the flight. Military aircraft on alert status could be subject to long periods of low temperature ground exposure (cold soak) prior to the start of mission. Since the final (end of mission) fuel temperature and percent hold-up depend to some extent on the initial bulk temperature, fuel preconditioning was included in the thermal analysis. Surface temperature records were searched for minimum and maximum temperatures on the preceeding day, at the latitude and longitude of the mission starting point. These data were used to provide 24 hours of temperature conditioning of the fuel, starting at takeoff minus 24.0 hours with a uniform fuel tank temperature of $10^{o}C$ (arbitrary) and an ambient temperature of $10^{o}C$ (arbitrary). The outside temperature was varied linearly to the day's maximum recorded temperature (assumed to occur at -12.0 hours) and then linearly to the day's minimum temperature at takeoff time, thus generating a pre-flight time-temperature profile. Thermal analysis calculations were then performed for this 24 hour conditioning period to generate a developed fuel tank thermal profile at takeoff time. Twenty-four hours was considered sufficient for the fuel to reach thermal equilibrium with the environment.

An example of the cumulative effect of pre-conditioning the fuel temperature is shown in Figure 3-9. Without preconditioning, the initial profile is a uniform 10C; with preconditioning, the initial profile is non-uniform, with an average value of approximately -17C. The effect diminishes as the mission proceeds, but is still evident after seven hours of flight time.

3.4.4 Temperature Profile Results

Complete results of the fuel temperature calculations performed using the thermal analysis program are too voluminous for this report. Samples appear

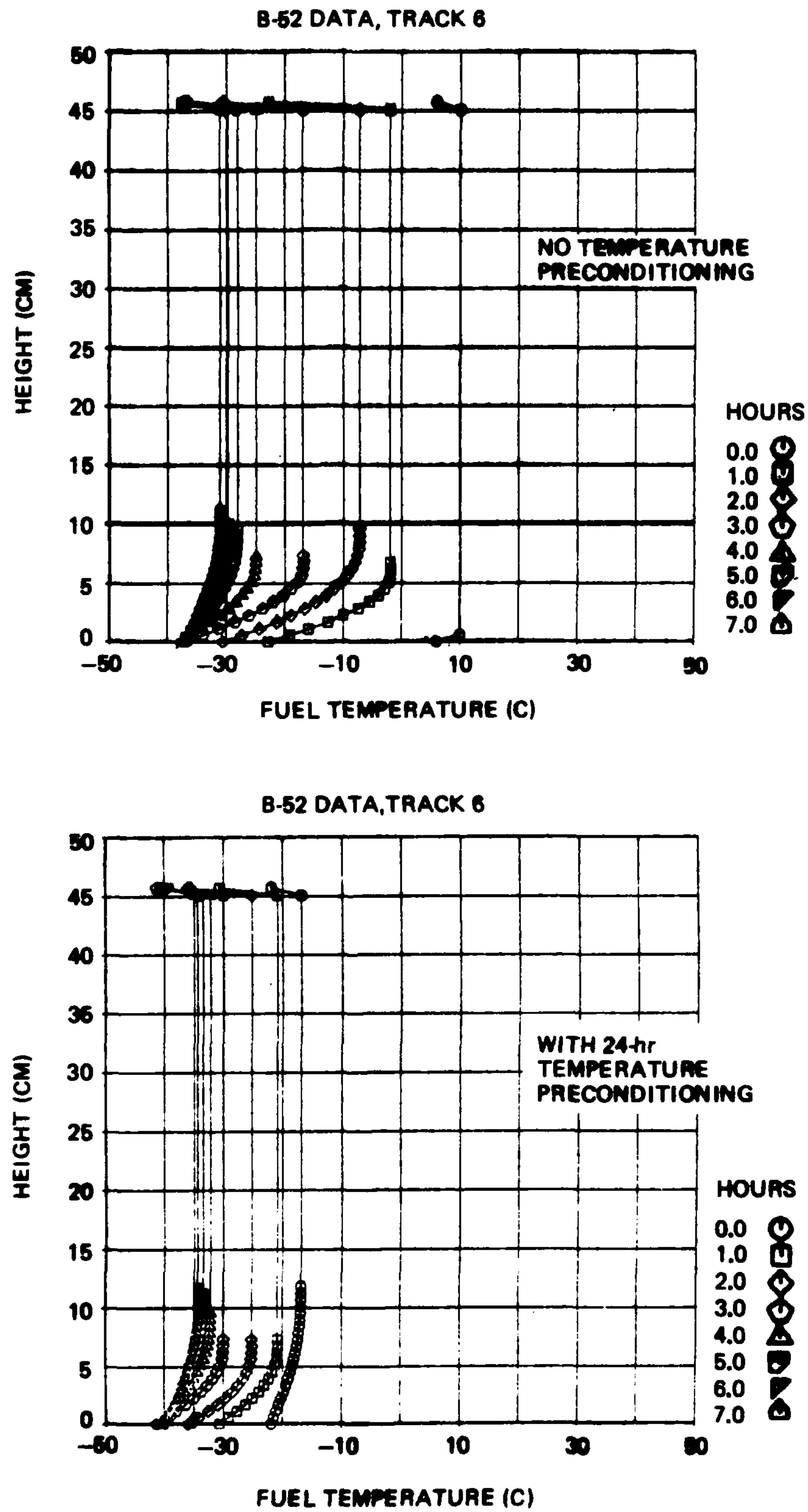


Figure 3-9. Effects of Preconditioning Fuel

in Appendix D. Several plots describe different phases of each mission; the time interval covered by each plot is identified in the right margin. The phases are described and in the following, and exemplified in Figure 3-10.

- o The effect of pre-conditioning the fuel because of thermal exposure prior to takeoff (Fig. 3-10A) is shown in the form of thermal profiles at four hour intervals beginning twenty-four hours prior to the flight and ending at takeoff time (-24 to 0 hrs.)

- o The effect of in-flight thermal exposure is shown in the form of thermal profiles at hourly intervals throughout the flight (Fig. 3-10B and C). In most cases more than one plot is required for visibility, since alternating cooling and warming cycles tend to cause overlapping in the profiles,

- o The development of the coldest fuel temperatures calculated occurred at the tank bottom; temperature profiles in this region are shown at twenty minute intervals in Figure 3-10D, which exhibit details of the lowest skin and bulk temperatures.

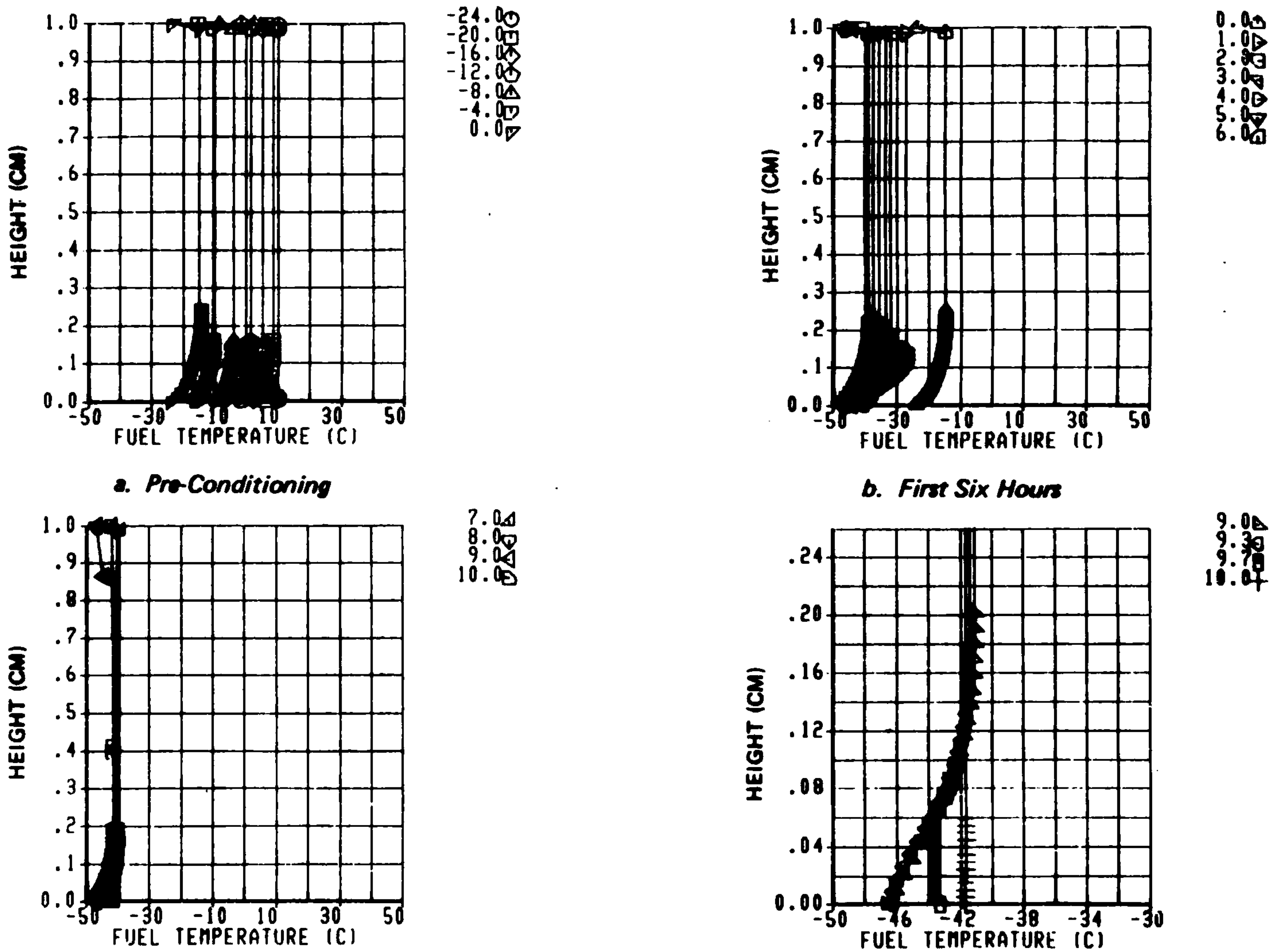
A review of the analytically derived profiles produced the following observations:

- o the lowest bulk (convection zone) temperature encountered in any flight was -41.5^{o}C,occurring in C-141 Track 8 approximately 10 hours into the flight, when the skin temperature had returned to -41.8^{o}C after reaching a low of -46.3^{o}C

- o pre-flight temperature conditioning of the fuel reduces the takeoff bulk fuel temperature an average of 20^{o}C from an initial temperature of 10^{o}C

- o the rate of heat transfer from the tank is greatly reduced after the fuel no longer makes contact with the upper wing surface. After this time, the ullage space which forms behaves as an insulator.

C-141, TRACK 8



a. *Pre-Conditioning*

b. *First Six Hours*

c. *Last Four Hours*

d. *Detail of Conduction Zone*

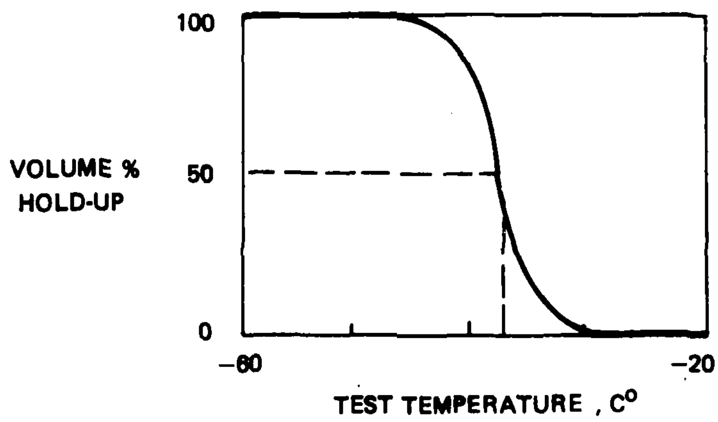
Figure 3-10. Typical Predicted Thermal Profiles

3.5 ESTIMATION OF LOSS OF AVAILABLE FUEL DUE TO FUEL FREEZING - TASK V

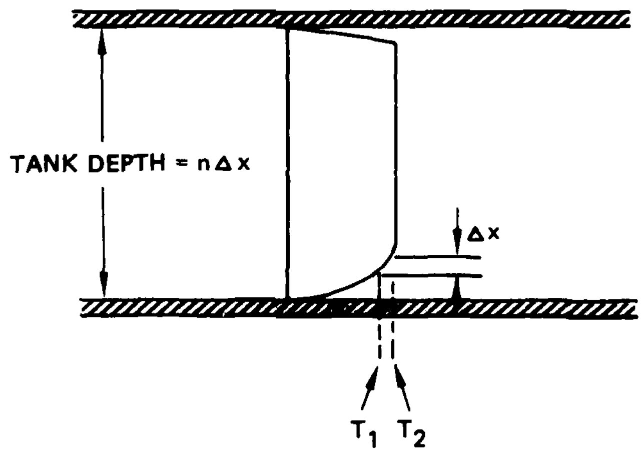
The first formation of frozen fuel will be along the wetted tank skins. In a full tank, if low temperatures are sustained, the entire upper and lower surfaces will be covered with a layer of frozen fuel which will thicken with increasing time. These layers of frozen fuel will interfere with convection processes, reducing heat transfer, and the latent heat of solidification will cause an apparent increase in specific heat of the freezing fuel. Thus the analytical model for calculating fuel temperature at this time is valid only in the absence of frozen fuel. Nevertheless, as a first approximation, temperature profiles generated from the all liquid fuel case are used to predict the mass of frozen fuel in the tank. This analysis is expected to be valid in the presence of small amounts of frozen fuel, but will become increasingly less accurate as frozen fuel builds up.

In addition to the thermal profile of the fuel in the tank, the hold-up calculations require information on the percentage of non-flowable (hold-up) fuel as a function of temperature in an isothermal fuel sample. The test device used to generate this data is known as a Shell-Thornton tester (Ref. 2). In this test, a 100 ml sample of fuel in a metal container is immersed into a constant low temperature bath long enough to reach thermal equilibrium. The container of fuel is removed from the bath, any remaining liquid fuel is drained, its volume measured, and the percent non-flowable fuel is calculated. The test is repeated at different bath temperatures for the construction of a hold-up curve; a typical Shell-Thornton test curve is shown in Figure 3-11a. The shape of the curve is strongly dependent on the fuel chemistry.

To calculate the amount of fuel hold-up in a fuel tank, the in-tank temperature profile is subdivided into N equal increments (Fig. 3-11b) and the average temperature, $T_{AVG} = 1/2(T_1+T_2)$, in each ΔX increment is calculated. Each ΔX layer is treated as isothermal to compute the percent hold-up from the Shell-Thornton curve, Figure 3-10. The mass of fuel hold-up in each layer is $\rho A \Delta X$, where A is the tank area. The mass percent of fuel hold-up in the tank is found by summing the hold-up mass (m_i) in each layer and dividing by the total mass in the tank,



a. *Typical Shell Thornton Curve*



b. *Diagram of Hold Up Calculation*

Figure 3-11. Hold-Up Estimation Procedure

$$\text{mass hold-up (\%)} = \frac{100}{m_t} \sum_{i=1}^{N} m_i \tag{4}$$

For LFP-14 fuel, the estimated hold-up for the most severe missions is presented in Figure 3-12. In general, the calculation over-estimates the hold-up, because as noted earlier, the calculation procedure used to generate the thermal profiles is based on a 100% liquid case. As noted earlier, frozen fuel on the top surface greatly reduces overall heat transfer from the tank; the data show that the effect becomes particularly noticeable above 10% hold-up. As a result, hold-up predictions of more than 10% exceeded those found experimentally.

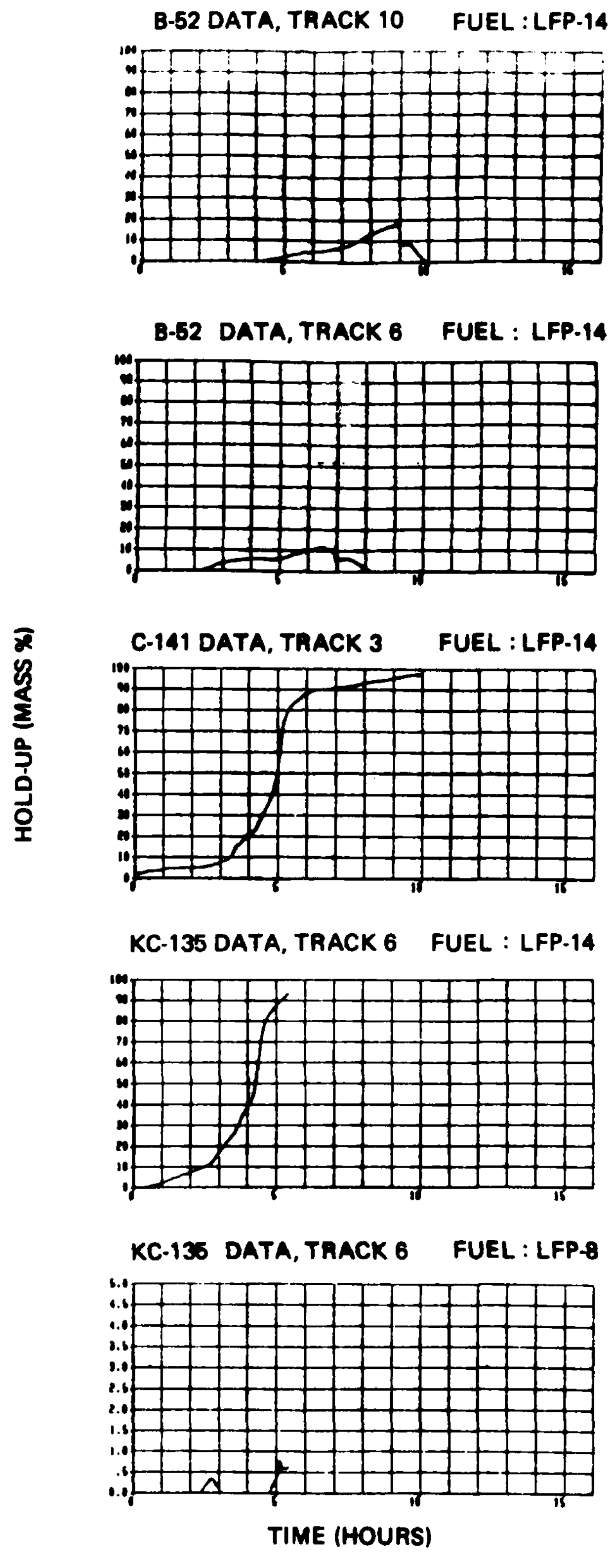


Figure 3-12. Predicted Hold-Up

4.0 EXPERIMENTAL VERIFICATION, TASK VI

A series of cold fuel tests were performed in the Boeing simulator tank (Fig. 4-1) to verify the predicted temperature profiles and to measure the percent mass hold-up expected for the "worst case" missions. While the analytical model does not account for the reduced heat transfer from frozen fuel in the tank, it permits a reasonably accurate estimate of the onset of solid deposits and their amount up to 10%.

4.1 TEST FUELS

Two test fuels, designated LFP-14 and JP-8/LFP-1 were selected because their freeze points (-34^{o}C and -43^{o}C respectively) are substantially higher than the maximum specification freeze points of the standard USAF JP-4, JP-5, and JP-8. The JP-8/LFP-1 is a blend of 13.7% LFP-1 and 86.3% JP-8 by volume. Fuel characterization data for these fuels are summarized in Table 4-1. Shell-Thornton (hold-up) measurements for each fuel are given in Figures 4-2 and 4-3.

4.2 TEST CONDITIONS

Four missions were selected for verification tests with each test fuel. These were: C-141 Track 8, KC-135 Track 6, B-52 Track 6 and B-52 Track 10. Since the analytical model predicts temperature profiles during warming conditions and as the tank is drained, it was desirable to include one run, B-52 Track 6, which simulated these conditions. The remaining tracks are the most severe low temperatures experienced for each airplane. Fuel usage was simulated by either gravity drain or intermittent switching-on of the simulator boost pump. Observation of the physical behavior of the hold-up fuel (formation, pumpability, and thawing) was of interest for analyzing operational effects.

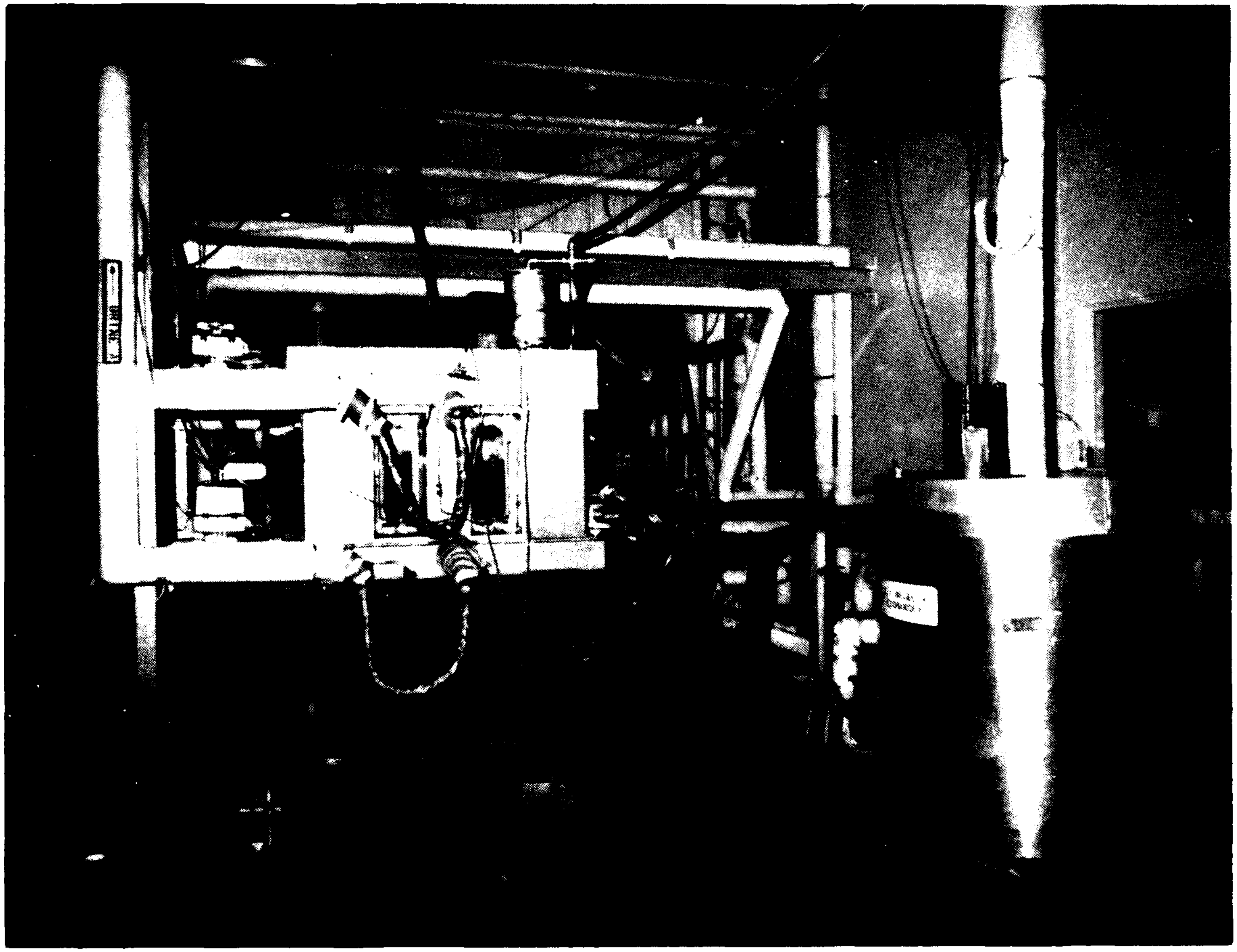


Figure 4-1. Photograph of Simulator Test Facility

Table 4-1 Fuel Analysis Data

PROPERTY		LFP-14 INTERMEDIATE FREEZE PT. KEROSENE	JP-8/LFP-1
SPECIFIC GRAVITY (60/60°F)		0.8079[d]	(86.3%/13.7% mix)
WATER CONTENT (KARL-FISHER) ASTM D1744		80 ppm[a]	c
FREEZING PT. ASTM D2386		-34°C±1°C[a),b]	-42.8°C
POUR PT. ASTM D-97		-35°C[a]	-48.3°C
BTU/LB ASTM D-86		19, 811[a]	c
DISTILLATION	I.B.P., °C	152.2[a]	c
	5%	180.0	
	10%	197.8	
	20%	205.0	
	30%	211.1	
	40%	216.7	
	50%	223.3	
	60%	230.0	
	70%	237.2	
	80%	247.8	
	90%	264.4	
	95%	281.7	
END POINT		290.0	
RECOVERY % VOL		98.	
RESIDUE % VOL		2.0	
LOSS		0	

a) Performed by E. W. Saybolt & Co, Inc. 6/16/81

b) Performed by Catholic University

c) Unknown

d) Reported by NASA-Lewis

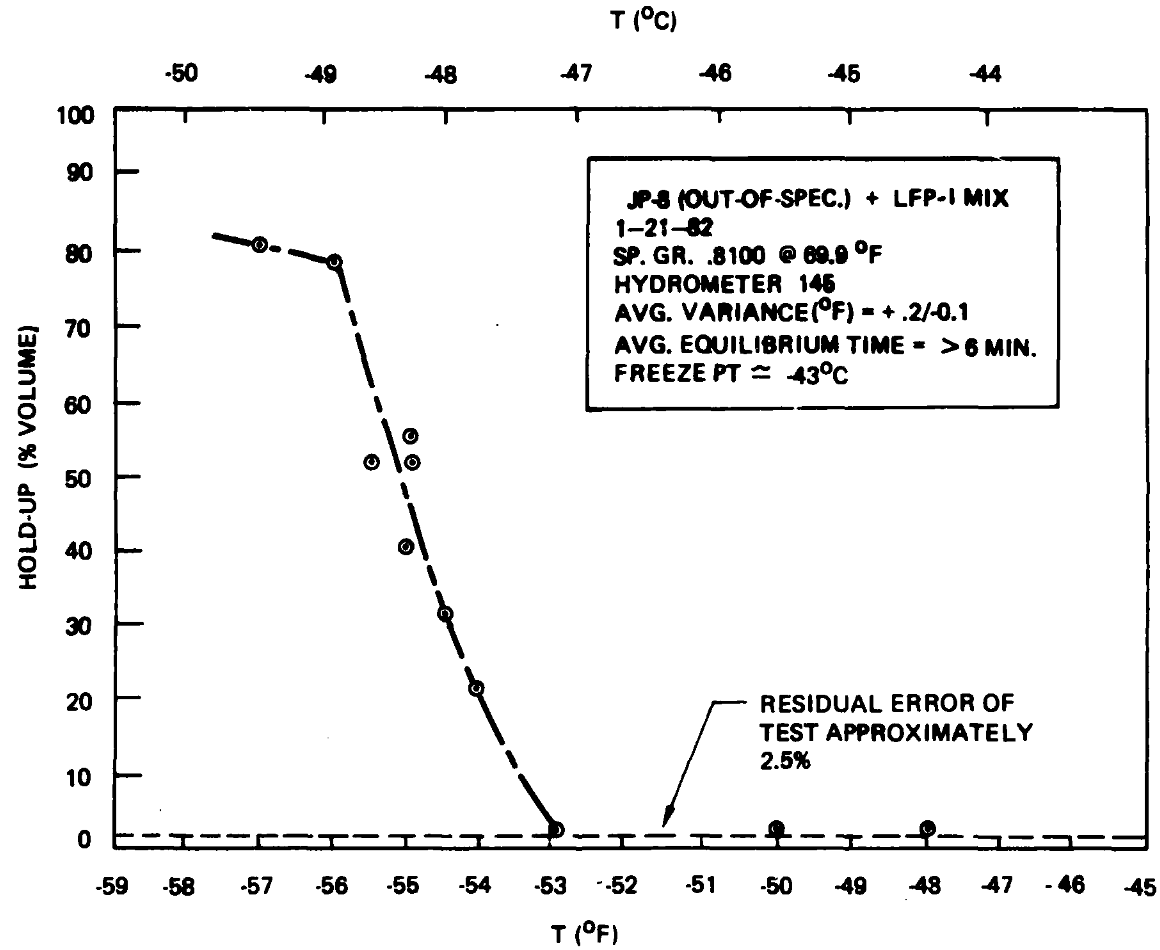


Figure 4–2. Shell Thorntorn Test Data, JP-8/LFP-1 Mixture

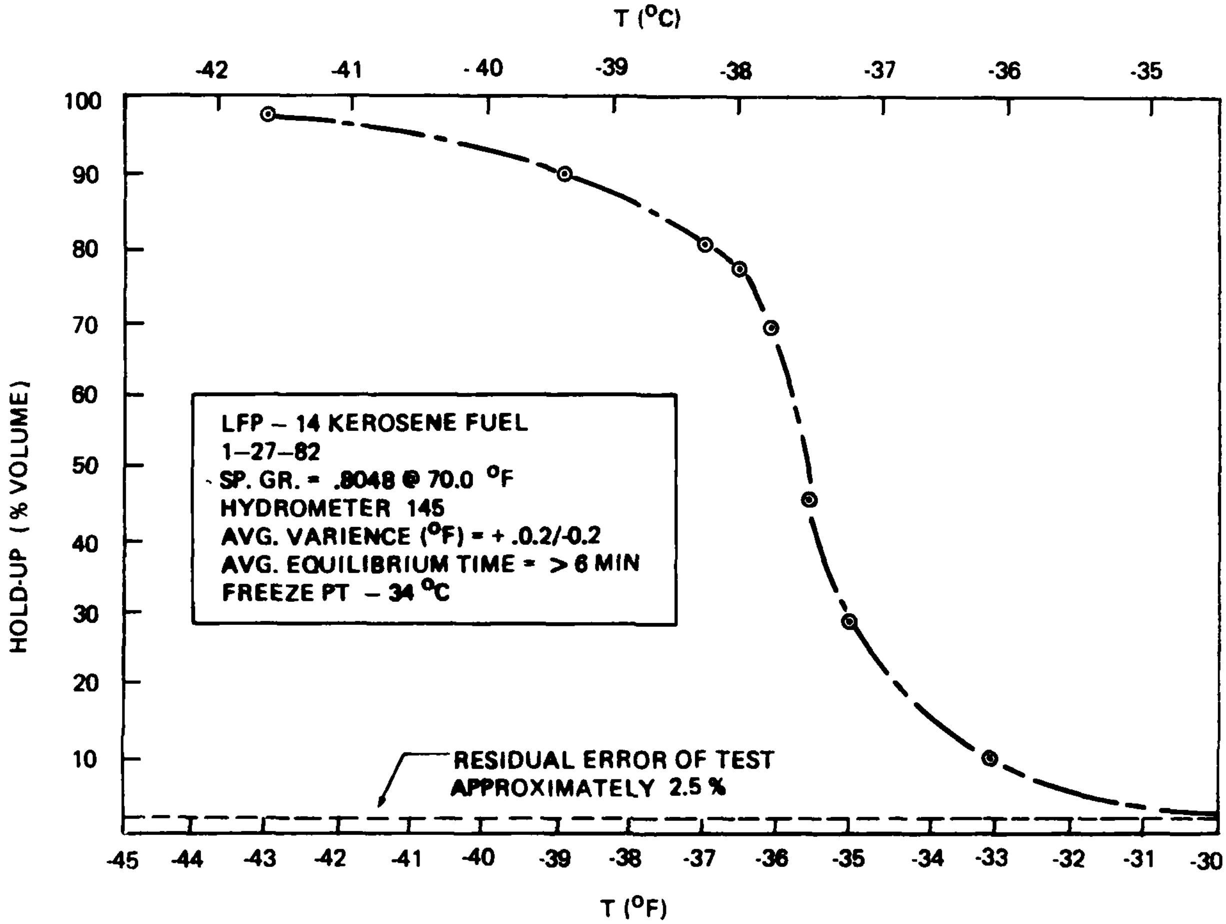


Figure 4–3. Shell Thornton Test Data, LFP-14

4.3 TEST SET-UP

The test set-up is shown schematically in Figure 4-4, and the tank internal arrangements are shown in Figures 4-5 to 4-8. Additional details of the fuel simulator and ancillary equipment are given in Reference 2.

Simulation of the upper and lower skin surface temperature is achieved by pumping refrigerant (chilled methanol) through the upper and lower skin cooling chambers. Flow control valves, A6 and A7, are automatically controlled to achieve the desired (mission) skin temperature which is programmed on the temperature data track. The automated control system is capable of producing equal upper and lower skin temperatures within about $\pm 1^{o}C$, and follows the programmed thermal profile very closely, Section 4.5. Additional instrumentation was provided for monitoring all test control parameters. An 11 liter auxiliary tank located on top of the simulator compensates for fuel contraction during cooling and keeps the tank full of liquid, i.e. prevents an ullage space from forming during cool down.

4.4 TEMPERATURE PROFILES

Characteristic temperature profiles were measured inside the simulator tank with chromel/alumel thermocouples distributed as shown in Figure 4-9. Over the range of test temperatures, the estimated uncertainty of the temperature measurements is $\pm 1.1^{o}C$. The HP3052A data acquisition system shown in Figure 4-10 recorded time, thermocouple output, and load cell readings. The data system provided printed paper tape output for "quick look" and cassette tape for data analysis. The cassette tape was converted to a 9-track magnetic tape which was used for analysis.

4.5 TEST PROCEDURES

The skin temperature profile for each mission was transcribed to a temperature data tape for control purposes. Each test run was started when the skin temperature and bulk liquid temperature were both within $\pm 2.8^{o}C$ ($\pm 5^{o}F$)

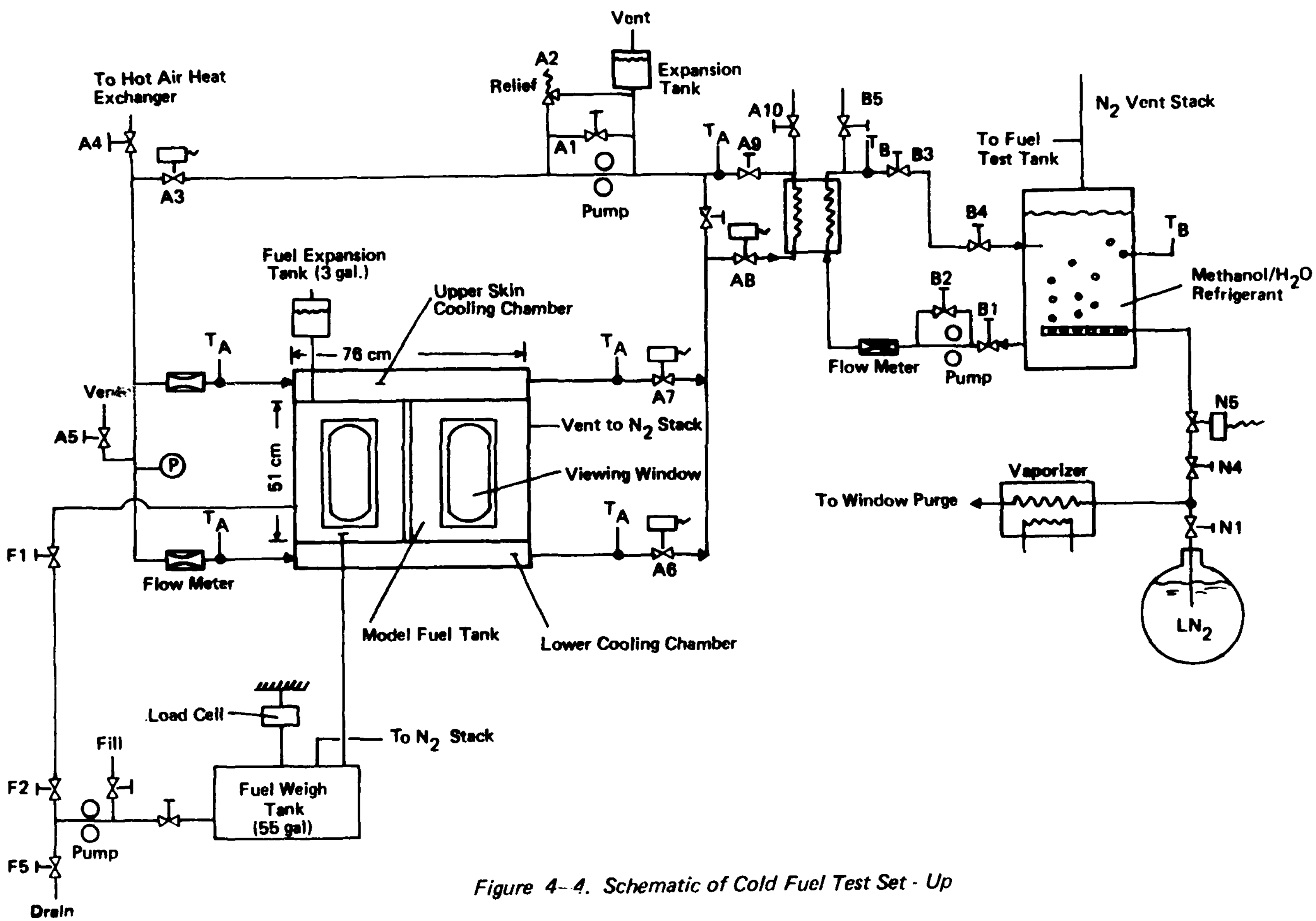


Figure 4–4. Schematic of Cold Fuel Test Set - Up

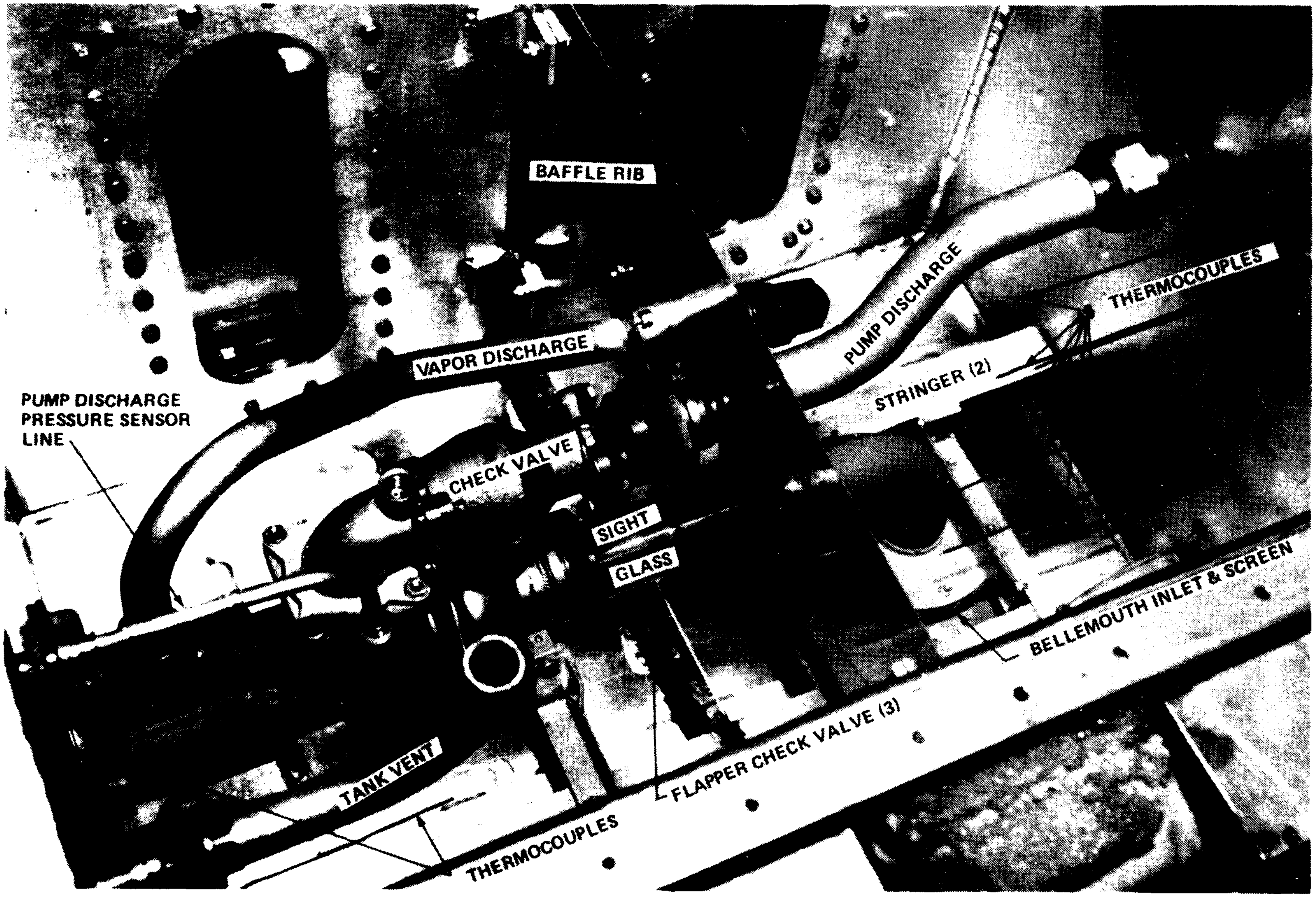


Figure 4-5. Interior of Fuel Tank Simulator

Photo No. 82 FK 00081-10

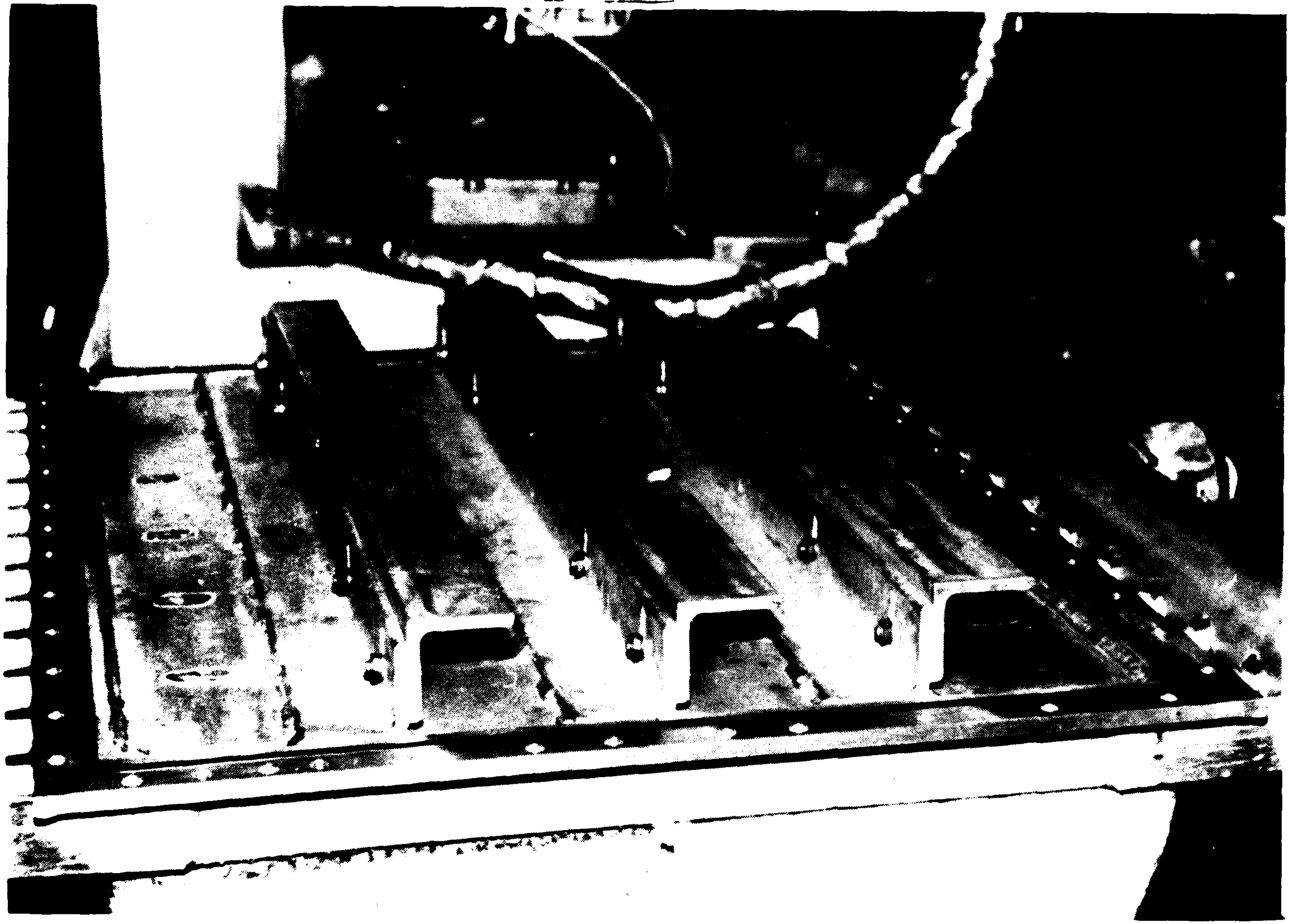


Figure 4–6. Photograph of Bottom Surface of Simulator Tank, Showing Ribs 3 inches High.

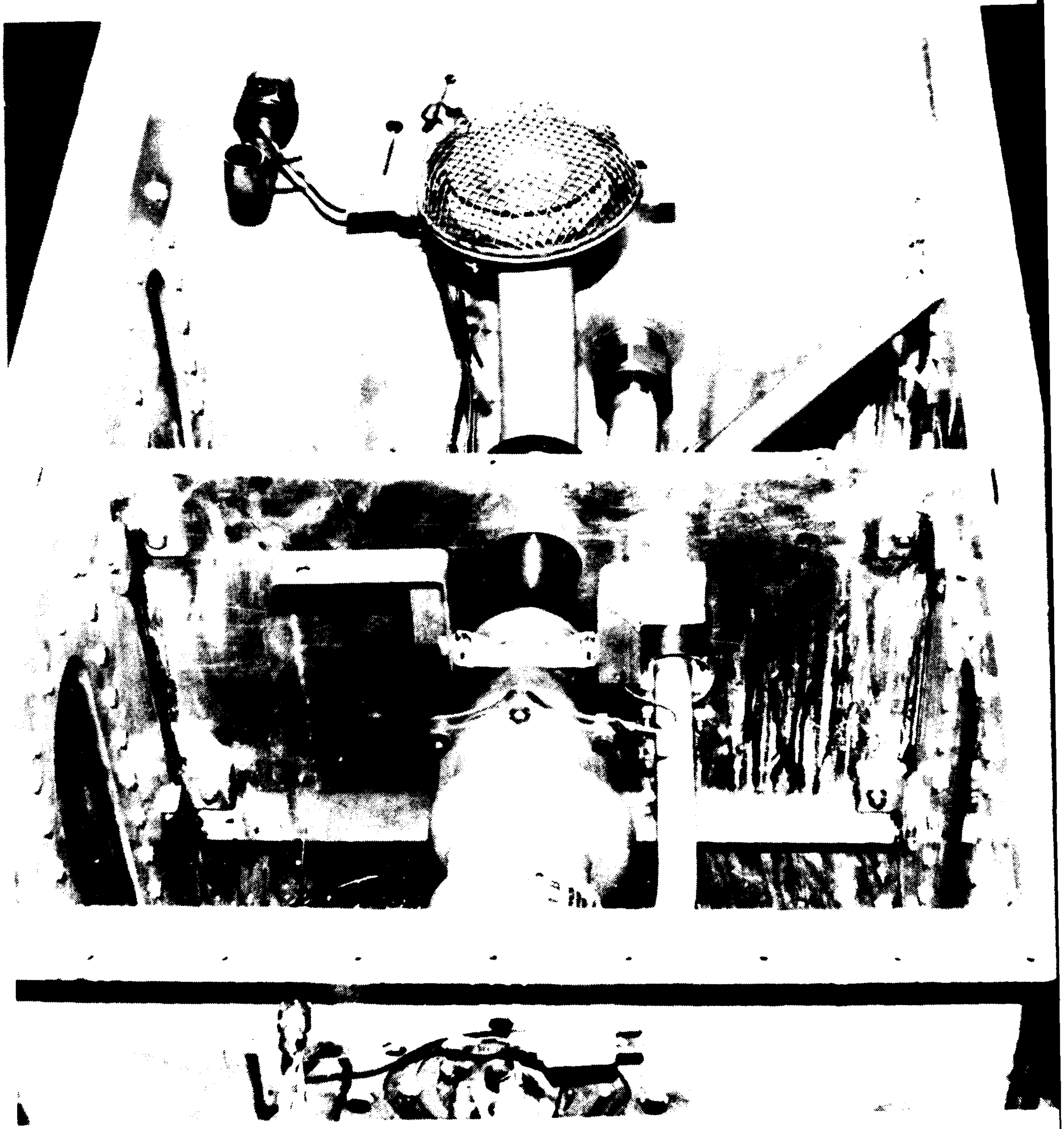


Figure 4–7. Bottom View of Simulator Tank, Showing Boost Pump Inlet and Drain (Vent) Line.

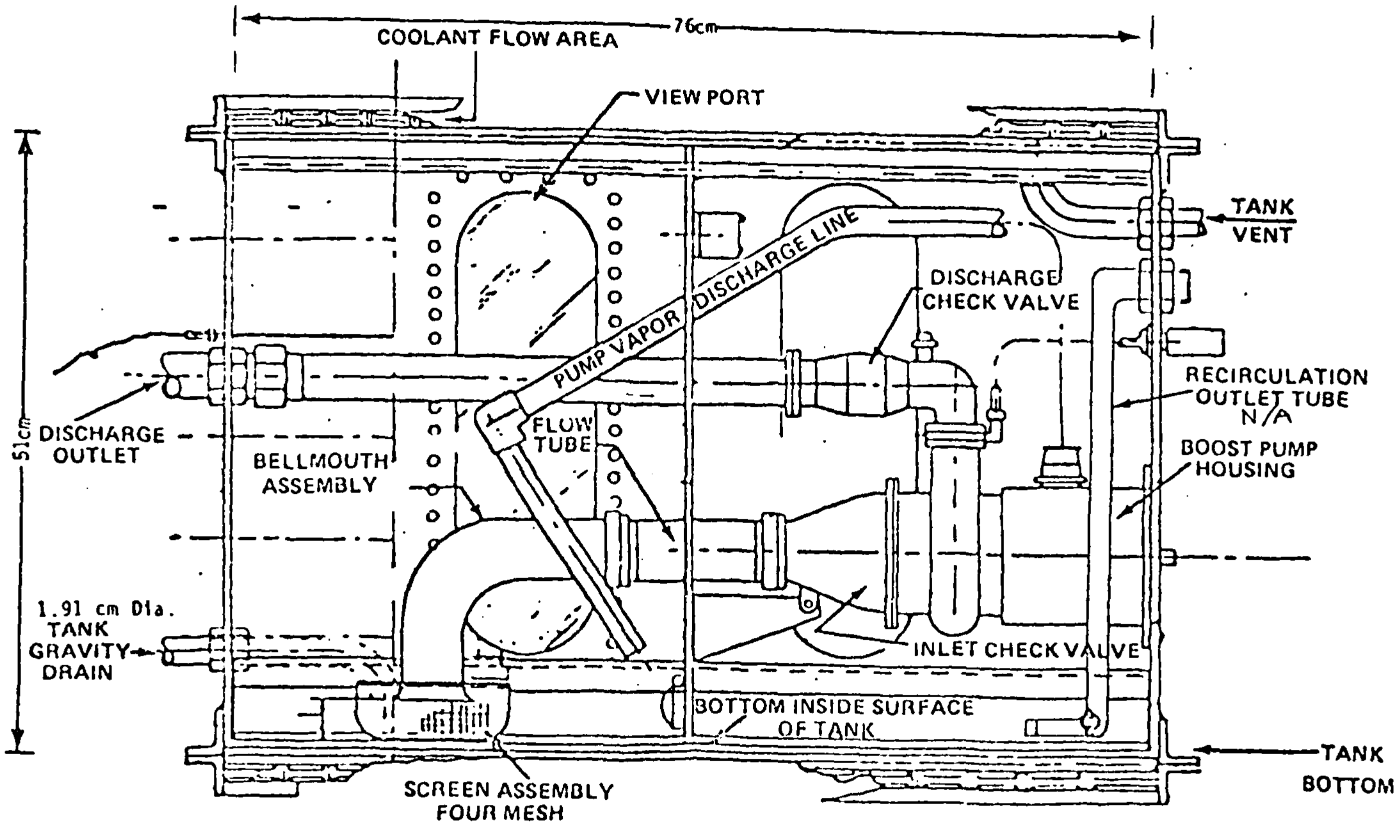


Figure 4-8. Cross Section View of Thermal Simulator Test Tank

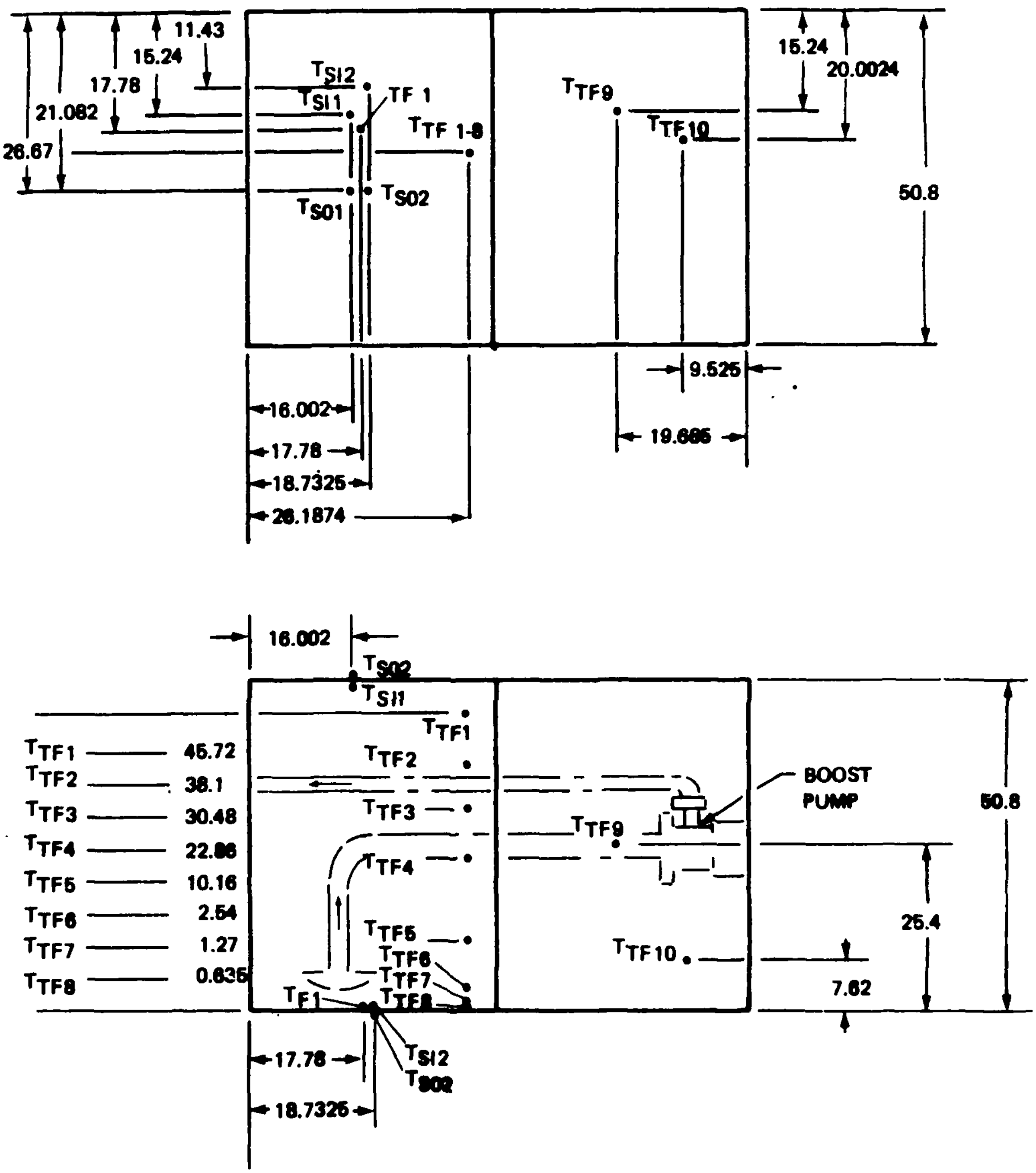


Figure 4-9. Fuel Tank Simulator Thermocouple Locations, Dimensions in cm

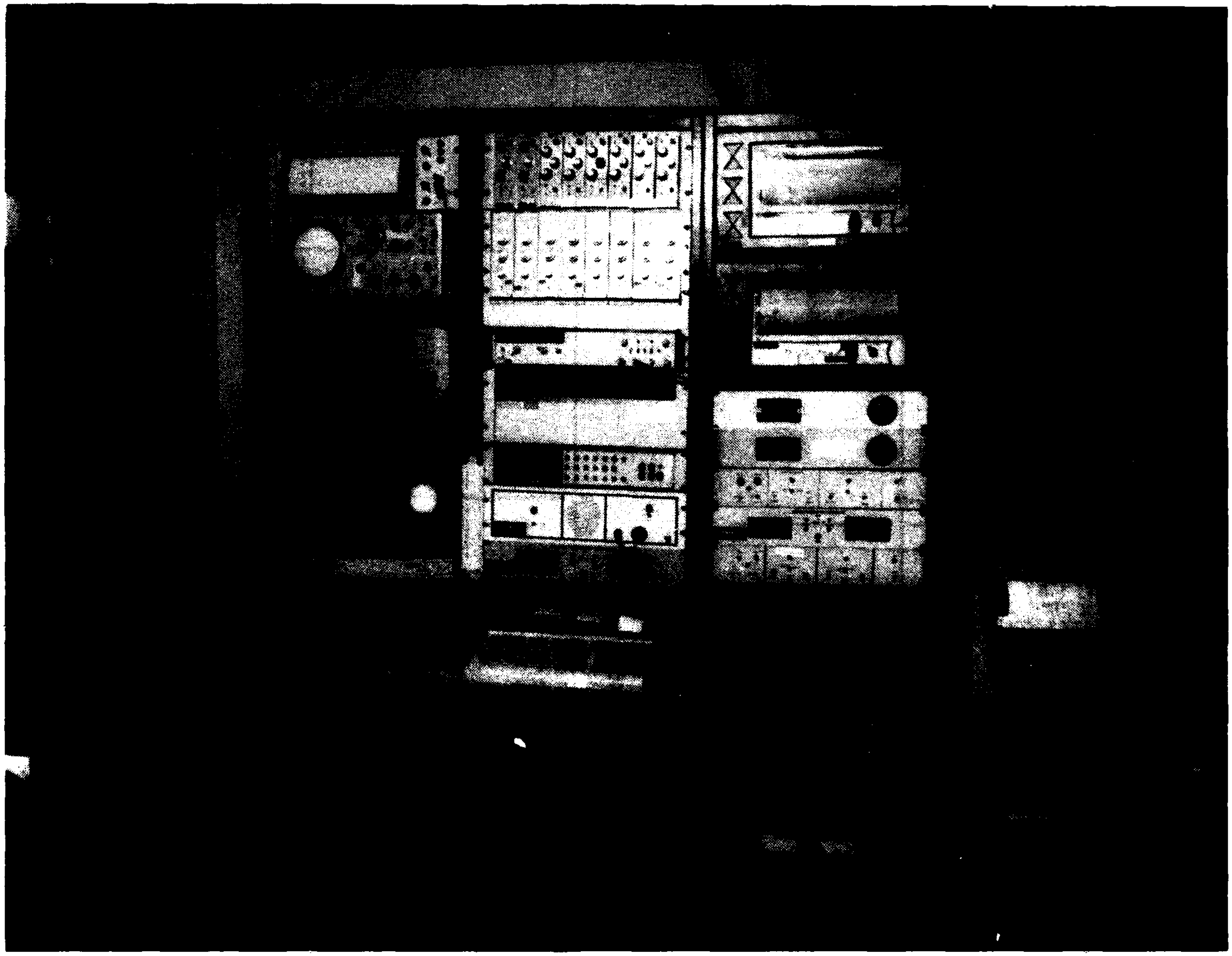


Figure 4-10. Photograph of Data Acquisition System

of the predicted pre-takeoff values. Figure 4-11 shows a typical skin temperature mission profile. Data were recorded at 5 minute intervals during the mission, except during the relatively short drain preceding hold-up measurements, when data were recorded every minute. Hold-up was measured at the "worst case" temperature profile of each mission, at which point the liquid was drained (by gravity) from the tank and its weight recorded by a load cell. Hold-up is defined as the fuel remaining in the tank after gravity drain and includes both solid and trapped liquid amounts. With liquid fuel in the tank, the visibility in the tank became progressively poorer as the temperature dropped, and photographs were not feasible. At the lower temperatures, the fuel became a very "waxy" dark yellow color. Additional tank lighting and attempts to remove water from the fuel by bubbling dry nitrogen through the fuel prior to loading the simulator did not improve the visibility at the low temperatures. It is believed that microscopic wax crystals form as the fuel temperature drops, eventually making the fuel opaque. After draining the tank, photographs were taken of the solid fuel as viewed through the windows in the simulator.

After measuring hold-up the skin temperature was increased to a value substantially higher than the freeze point. The tank was drained of the residual fuel and a mass balance performed.

4.6 RESULTS

This discussion is divided into two subsections. The first deals with time varying thermal profiles measured during mission simulation. The second deals with hold-up experimental measurements as determined by differential weighing.

4.6.1 Temperature Profiles

The measured temperature profiles, Figures 4-12 to 4-17, are generally in good agreement with the predicted profiles. The points plotted in these curves are the actual thermocouple measurements at the time specified. The line connecting the points is somewhat misleading, especially at the top of the profile; additional thermocouples in this region would undoubtedly have revealed a much sharper gradient, characteristic of natural convection. Comparisons of predicted and experimental temperature measurements are given

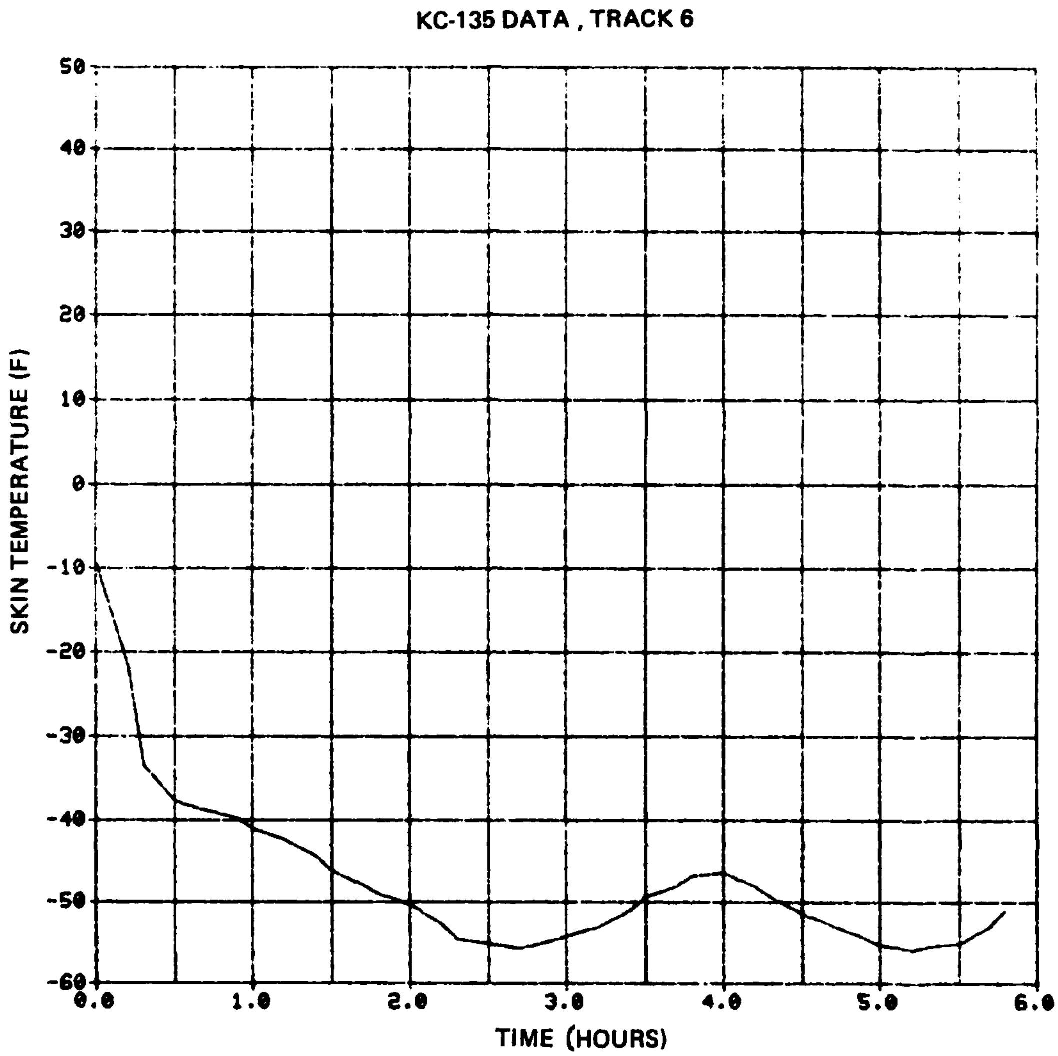
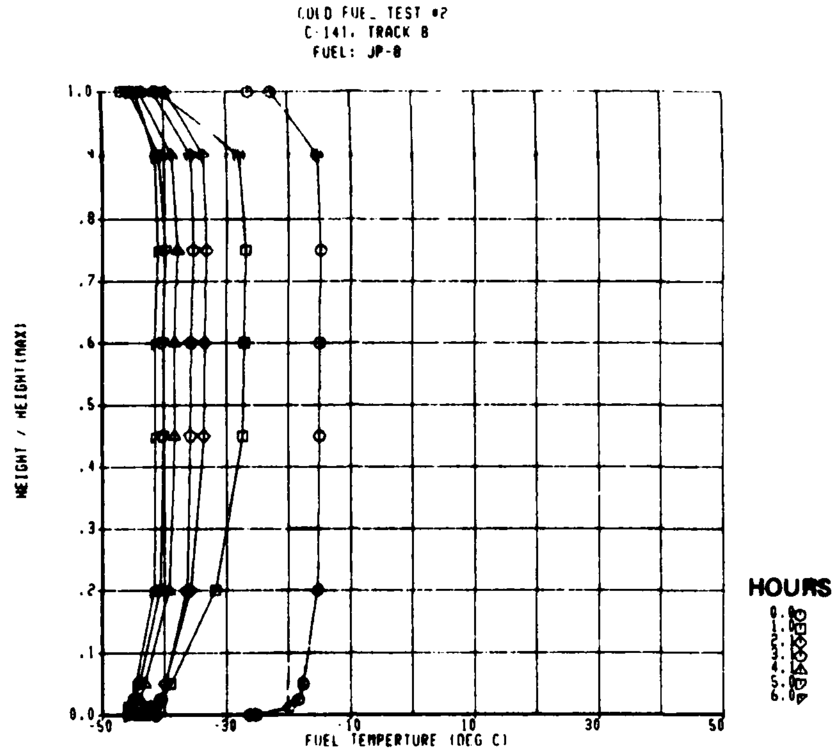
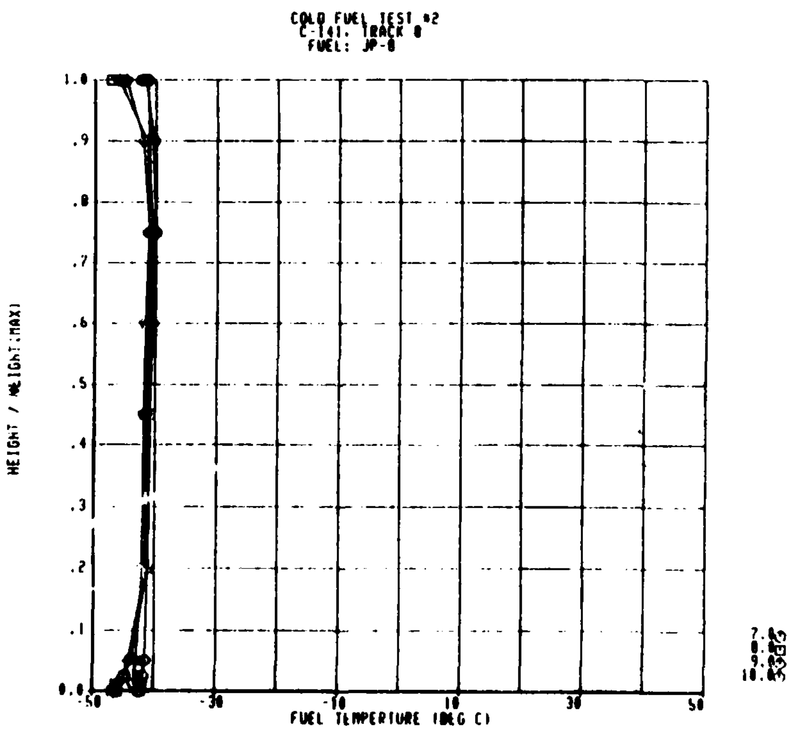


Figure 4-11. Typical Skin Temperature Profile

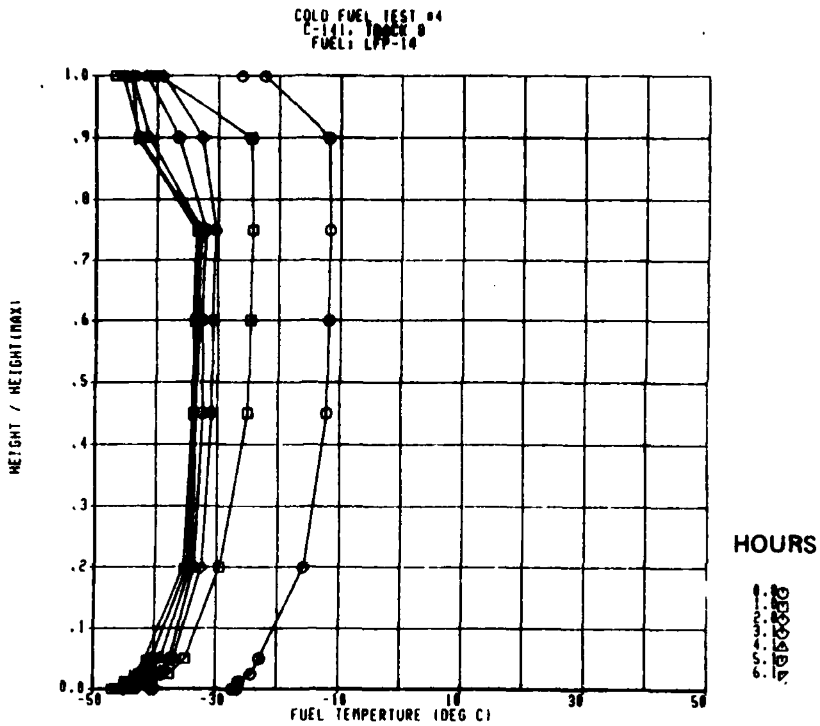


a. FIRST SIX HOURS

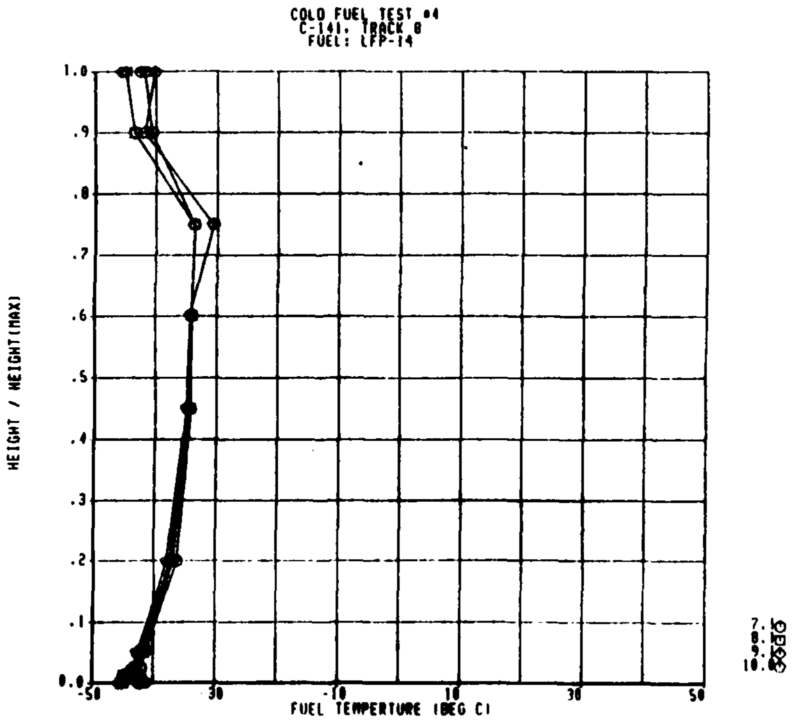


b. FINAL PORTION OF FLIGHT

Figure 4-12. Measured Temperature Profiles, C-141 Track 8, JP-8

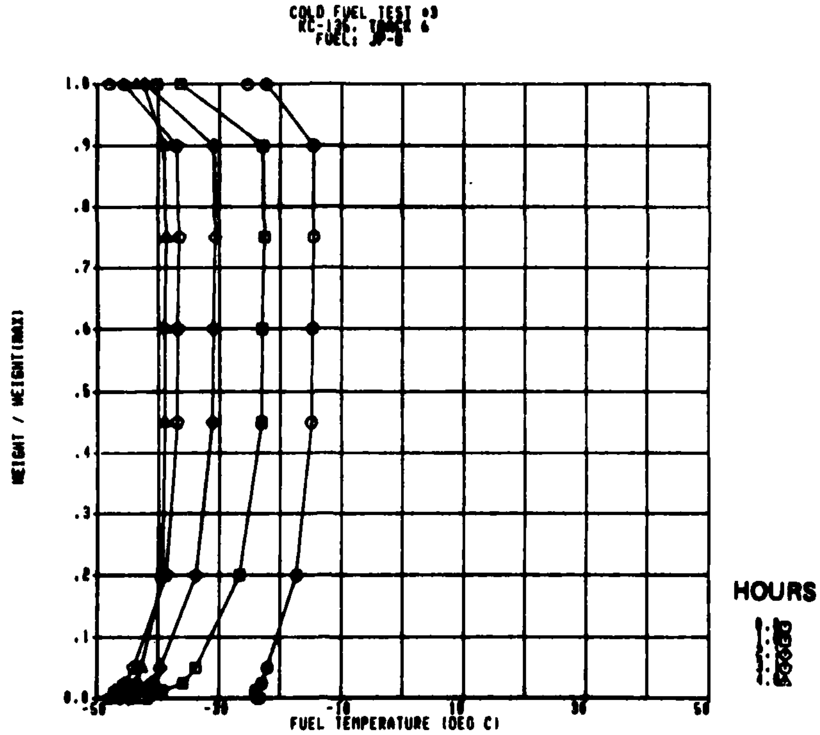


a. FIRST SIX HOURS

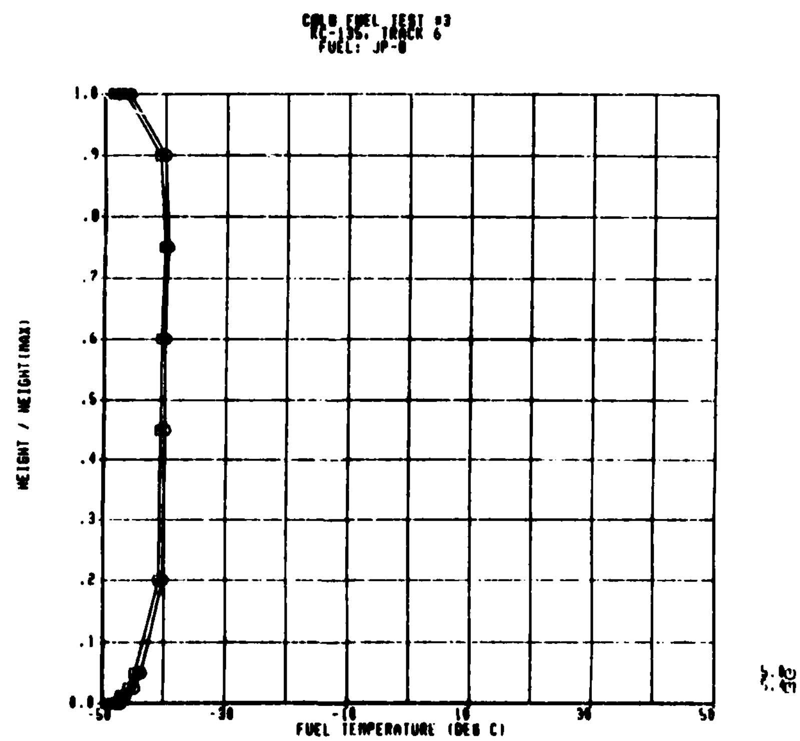


b. BALANCE OF FLIGHT

Figure 4-13. Measured Temperature Profiles, C-141 Track 8, LFP-14

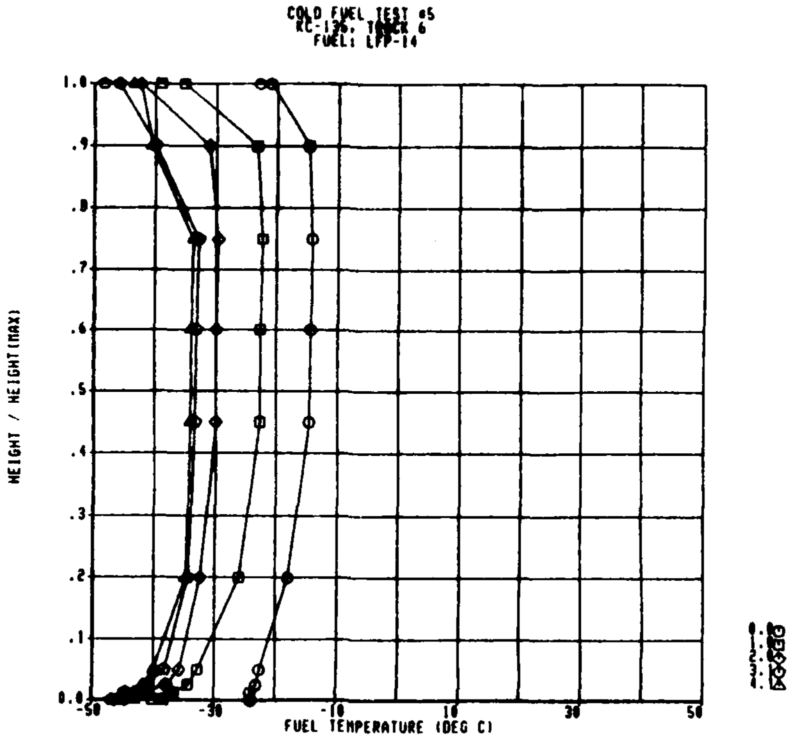


a. FIRST FOUR HOURS

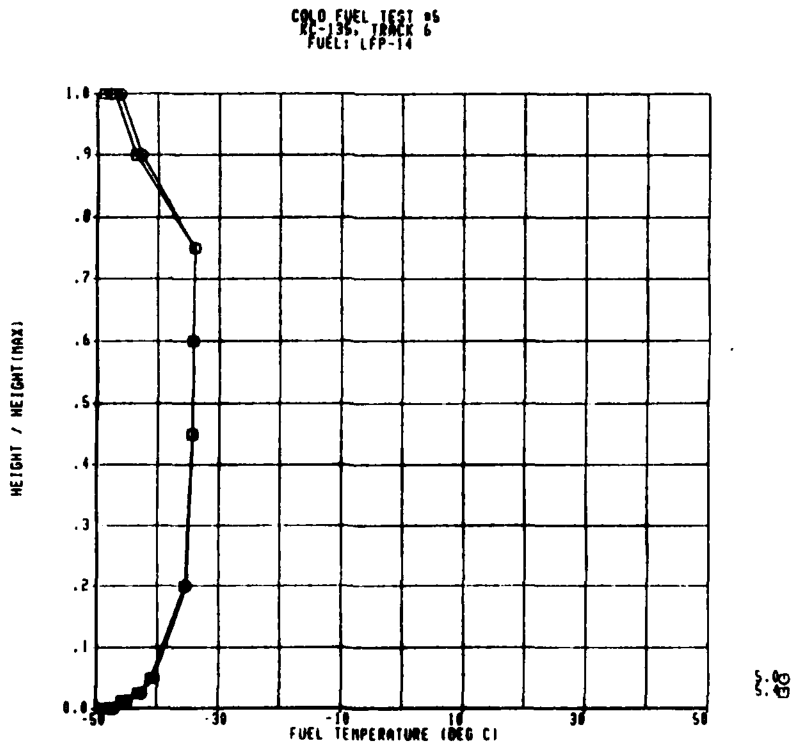


b. BALANCE OF FLIGHT

Figure 4-14. Measured Temperature Profiles, KC-135 Track 6, JP-8

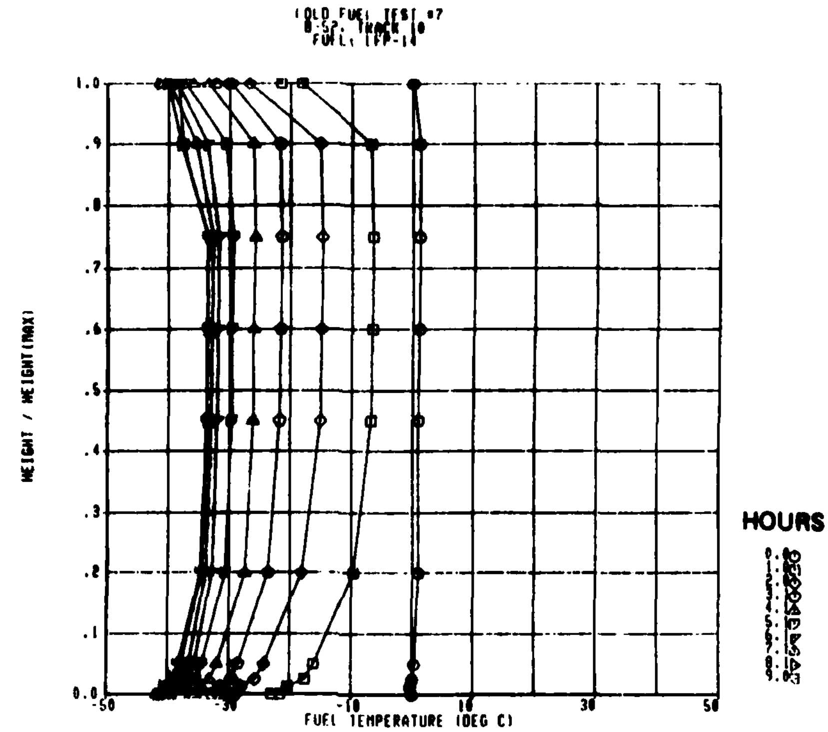


a. FIRST FOUR HOURS

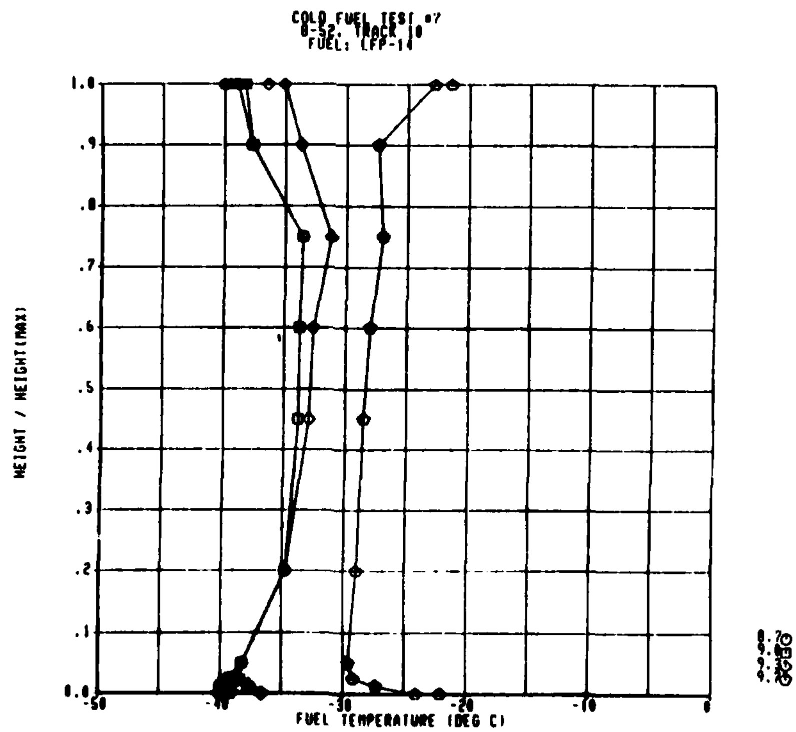


b. BALANCE OF FLIGHT HOURS

Figure 4-15. Measured Temperature Profiles, KC-135 Track 6, LFP-14

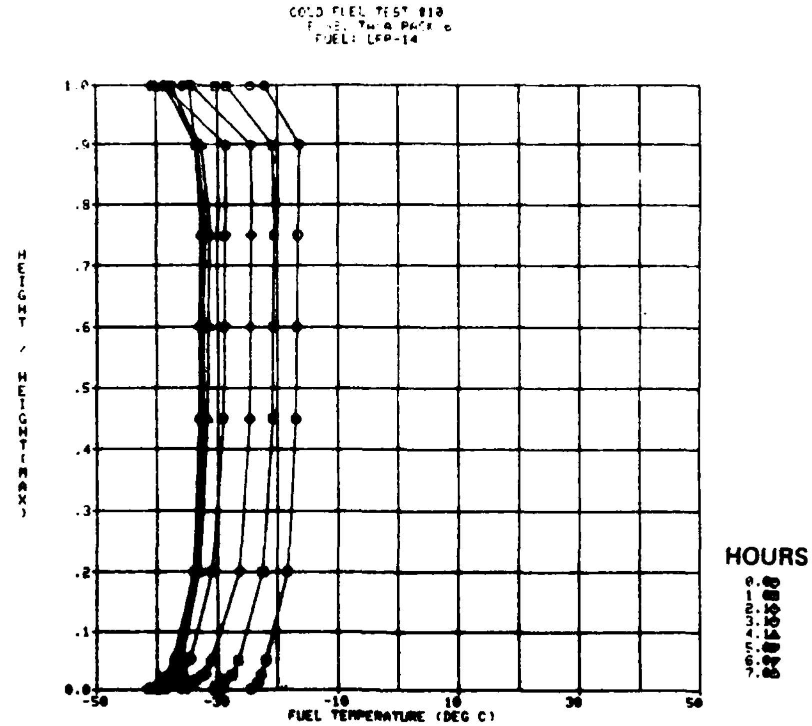


a. FIRST NINE HOURS

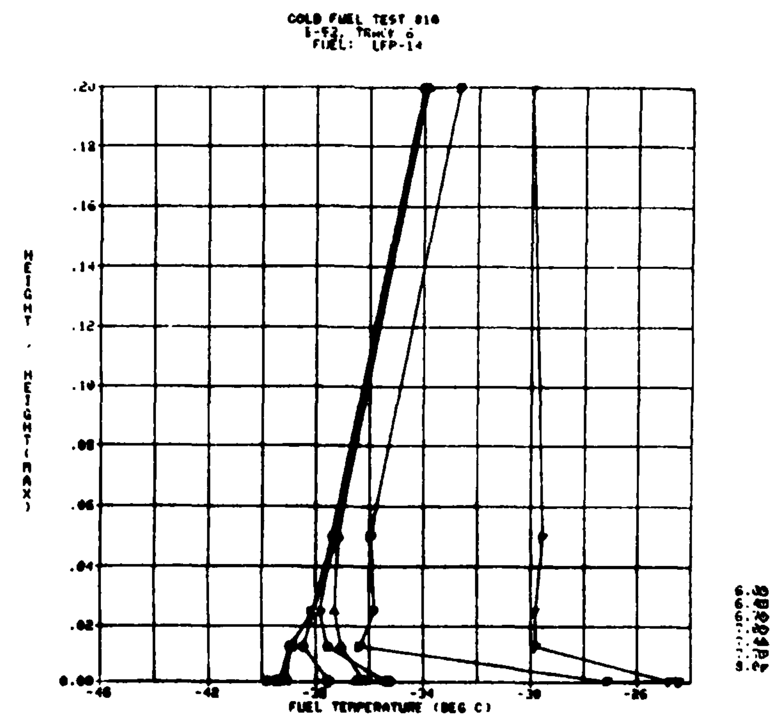


b. BALANCE OF FLIGHT

Figure 4-16. Measured Temperature Profiles, B-52 Track 10, LFP-14



a. FIRST SEVEN HOURS



b. BALANCE OF FLIGHT

Figure 4-17. Measured Temperature Profiles , B-52 Track 6, LFP-14

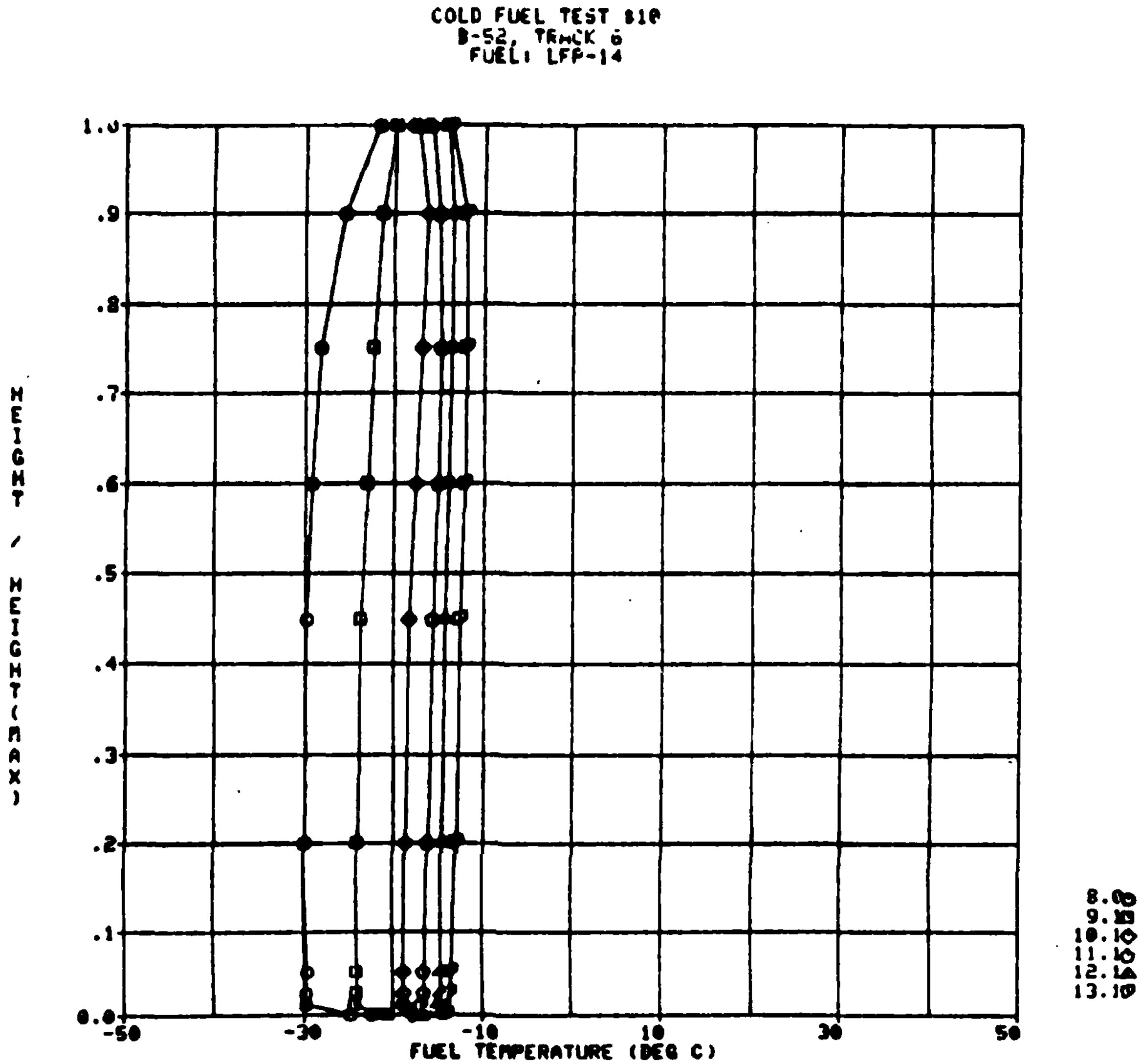


Figure 4-17. (Continued) Temperature Profiles, B-52 Track 6, LFP-14

in Figures 4-18 to 4-21. Predicted temperatures were typically within ±2^{o}C of those measured. Better agreement could have been achieved if the initial conditions had been more closely matched; in the experiment, it was difficult to exactly match the analytical profiles at the start of a test. Agreement was improved by using the experimental critical conditions as the starting point for an analytic solution (Fig. 4-22).

With frozen fuel in the tank, the temperature profiles diverged from those predicted in a full liquid tank. This was most evident with the higher freeze point fuel, LFP-14, in several of the tests (Fig. 4-18, 19, 21), where the insulation provided by the frozen fuel kept the measured temperatures in the mixing region well above those predicted (Appendix D).

4.6.2 Hold-Up

The hold-up measurements are summarized in Table 4-2. Recall that the hold-up measurements were all scheduled to occur at the time of lowest bulk fuel temperature as predicted analytically. Generally, the time of lowest bulk temperature occurs before fuel withdrawal from the study tank would begin, in-flight, as can be seen by reference to the last column of the table.

No hold-up was measured with the JP-8/LFP-1 blend test fuel during any of the experiments. Because of the insulating effect of frozen fuel, the measured hold-up with the LFP-14 fuel was less than predicted. For example, with LFP-14, C-141 Track 8 and KC-135 Track 6 hold-up was predicted to be in the range of 90-100%, while only 30% and 37% were measured. As expected, the majority of hold-up formed along the top and bottom surfaces of the tank. Photographs of the hold-up are presented in Figures 4-22 to 4-26. After draining the tank, approximately 80% of the hold-up was a slushy material located on the bottom of the tank; during the drain, frozen fuel on the upper surface was observed to release and collect at the tank bottom. When the tank was tipped the slush fuel tended to slump, with an apparent behavior similar to applesauce.

After liquid was drained from the tank, only 2 to 3% of the slush was pumpable, apparently because of flow blockage and cavitation in the suction

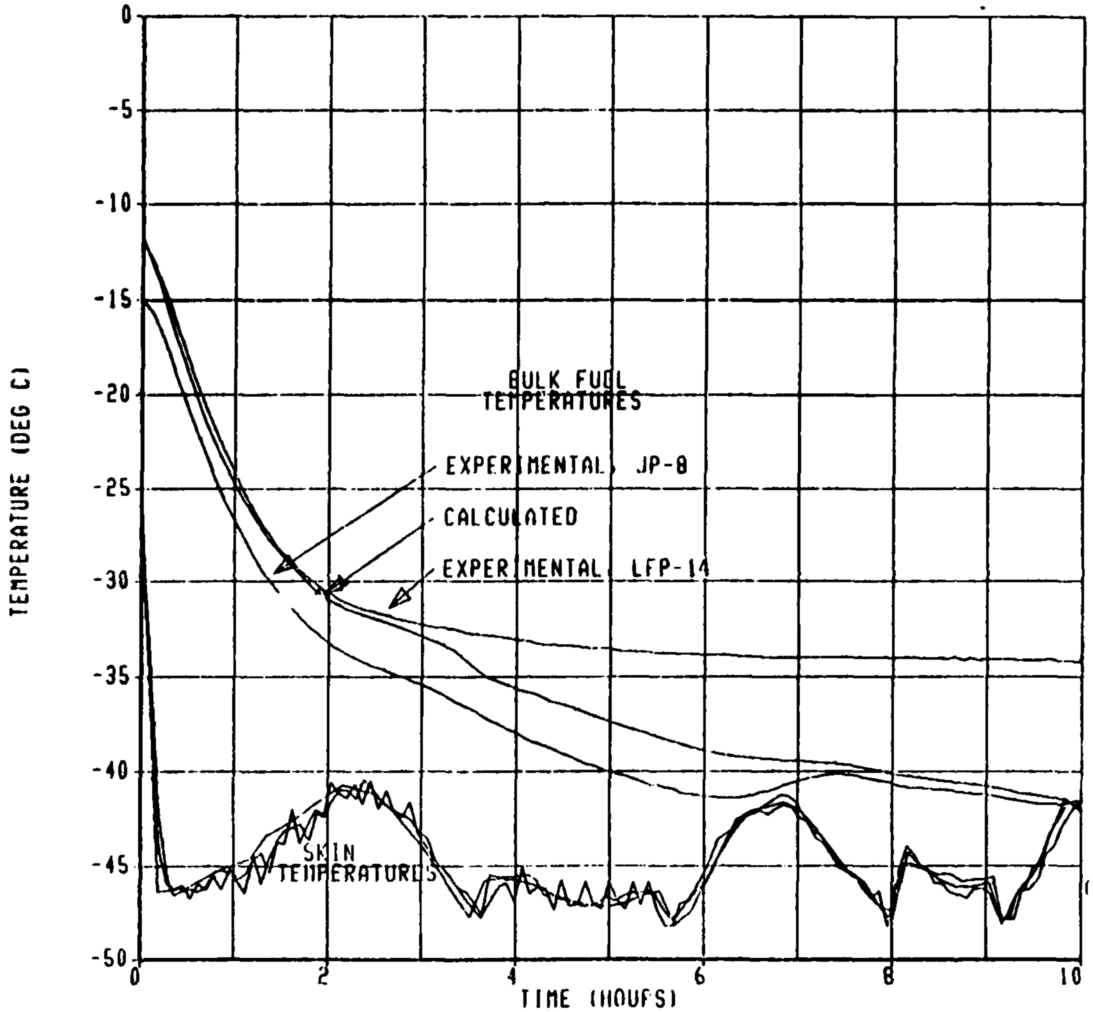


Figure 4-18. Comparison of Experiment and Analysis C-141 Track 8

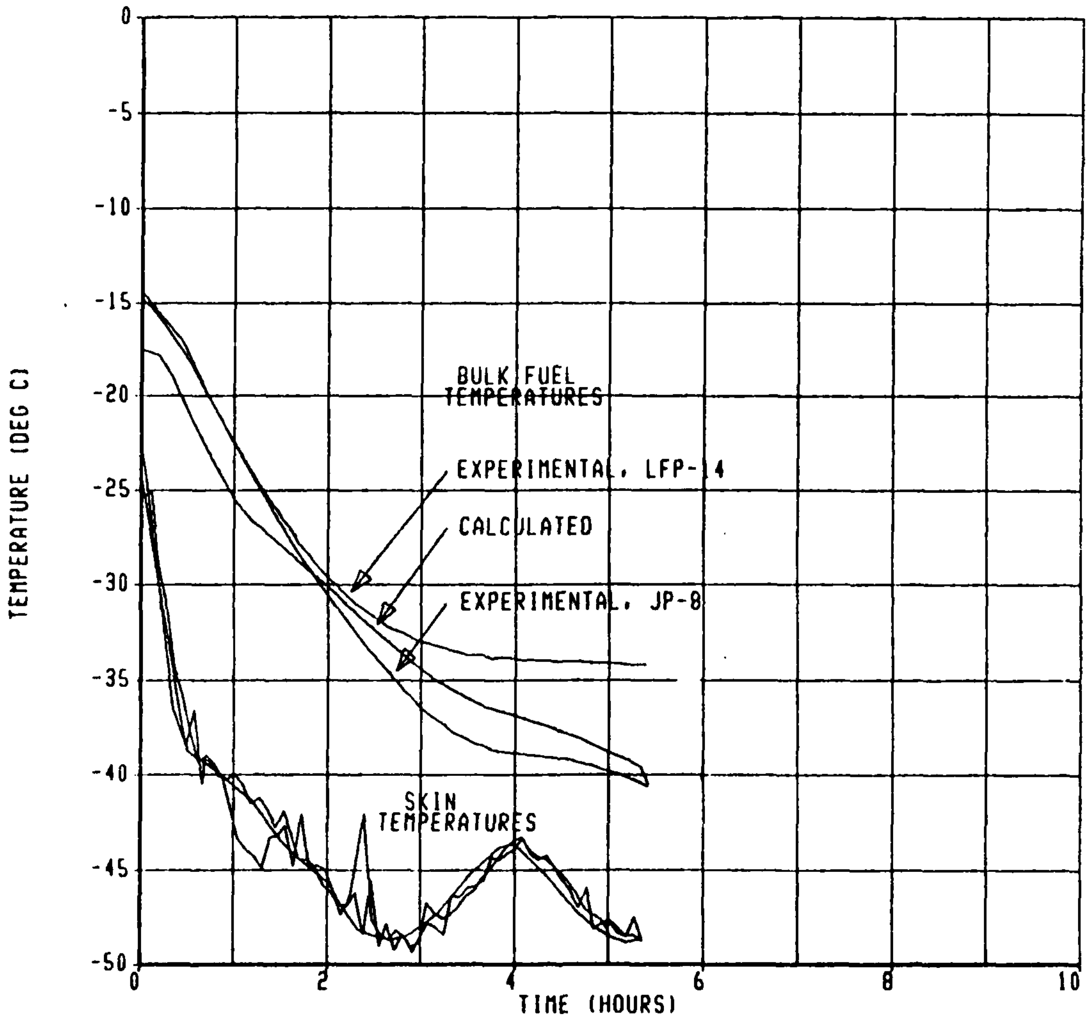


Figure 4-19. Comparison of Experiment and Analysis, KC-135 Track 6

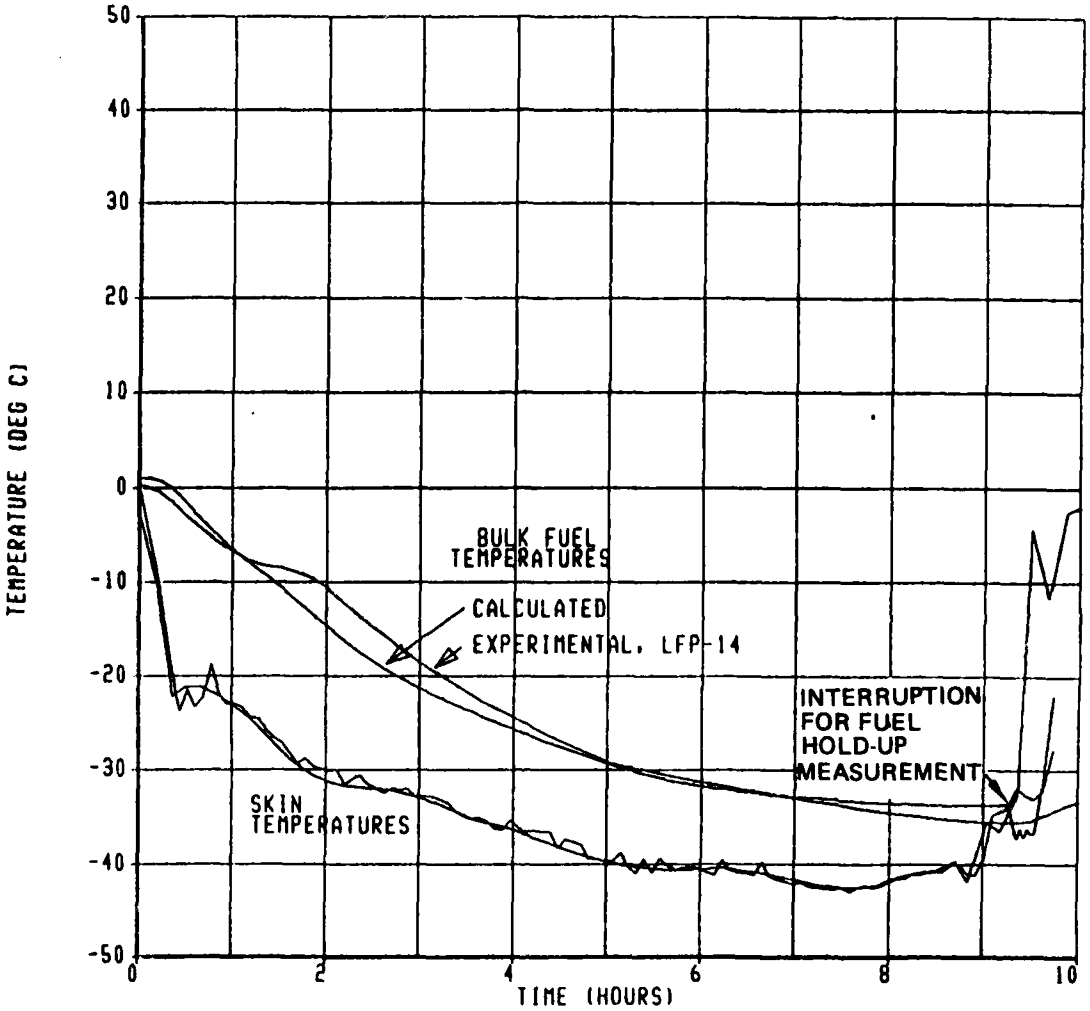


Figure 20. Comparison of Experiment and Analysis B-52 Track 10

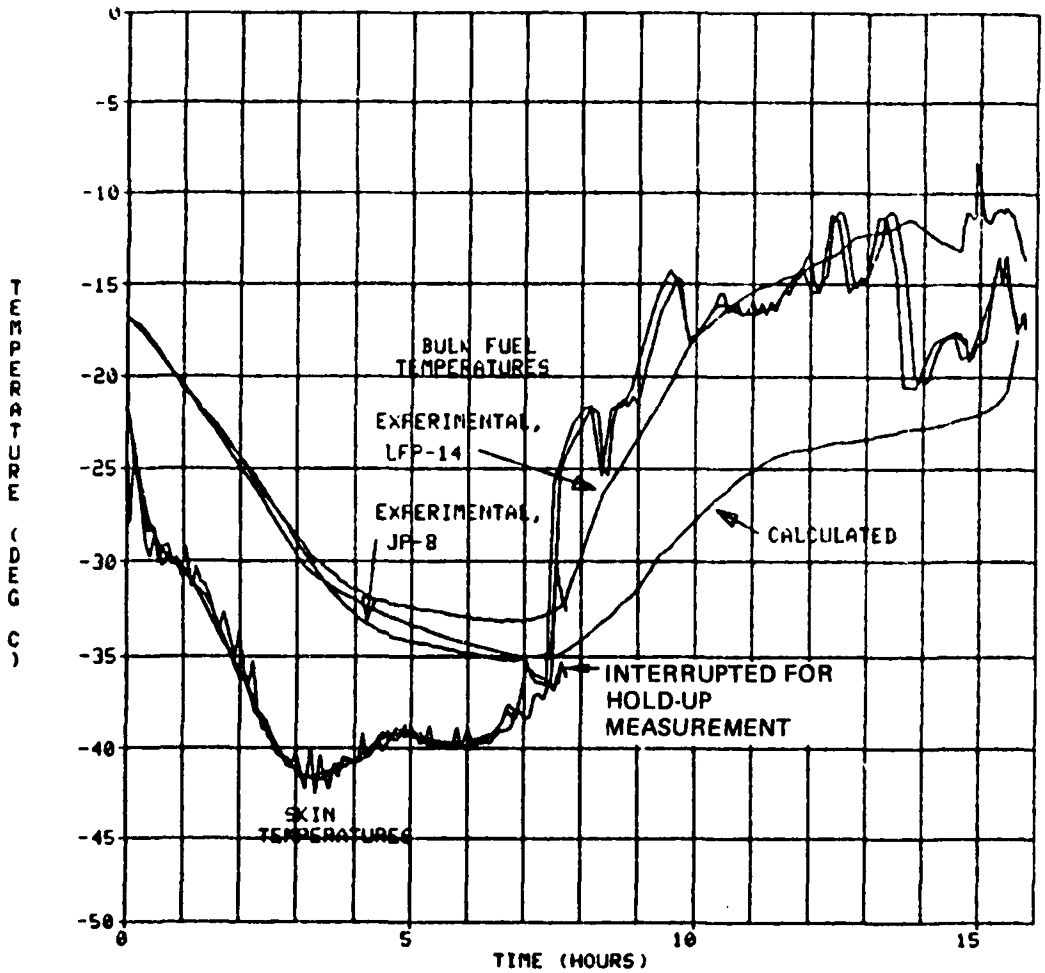


Figure 4-21. Comparison of Experiment and Analysis, B-52 Track 6

Table 4-2. Summary of Cold Fuel Hold-Up Tests

TEST NUMBER	TRACK	FUEL TYPE	TIME OF HOLDUP MEAS (Hrs)	T_{SKIN} (^{o}C)	T_{BULK} (^{o}C)	HOLD-UP MEASURED	TIME OF INITIAL FUEL WITHDRAWAL (HRS)
1	C-141, Track 8	JP-8	9.9	-42.8	-41.9	No Hold-Up	8.7
2	C-141, Track 8	JP-8	10.2	-46.8	-41.8	No Hold-Up	8.7
3	KC-135, Track 6	JP-8	5.9	-48.3	-41.3	No Hold-Up	5.2
4	C-141, Track 8	LFP-14	10.0	-41.7	-34.6	30% (By Mass)	8.7
5	KC-135, Track 6	LFP-14	5.7	-47.6	-34.4	37% (By Mass)	5.2
6	C-141, Track 8	LFP-14	10.1	-28.9	-34.4	Invalid Data	8.7
7	B-52, Track 10	LFP-14	9.3	-41.2	-33.8	No Hold-Up	14.6
8	C-141, Track 8	LFP-14	9.9	-42.2	-35.1	30% (By Mass)	8.7
9	B-52, Track 6	JP-8	7.5	-39.3	-35.2	No Hold-Up	14.6
10	B-52, Track 6	LFP-14	---	---	---	Not Measured	14.6

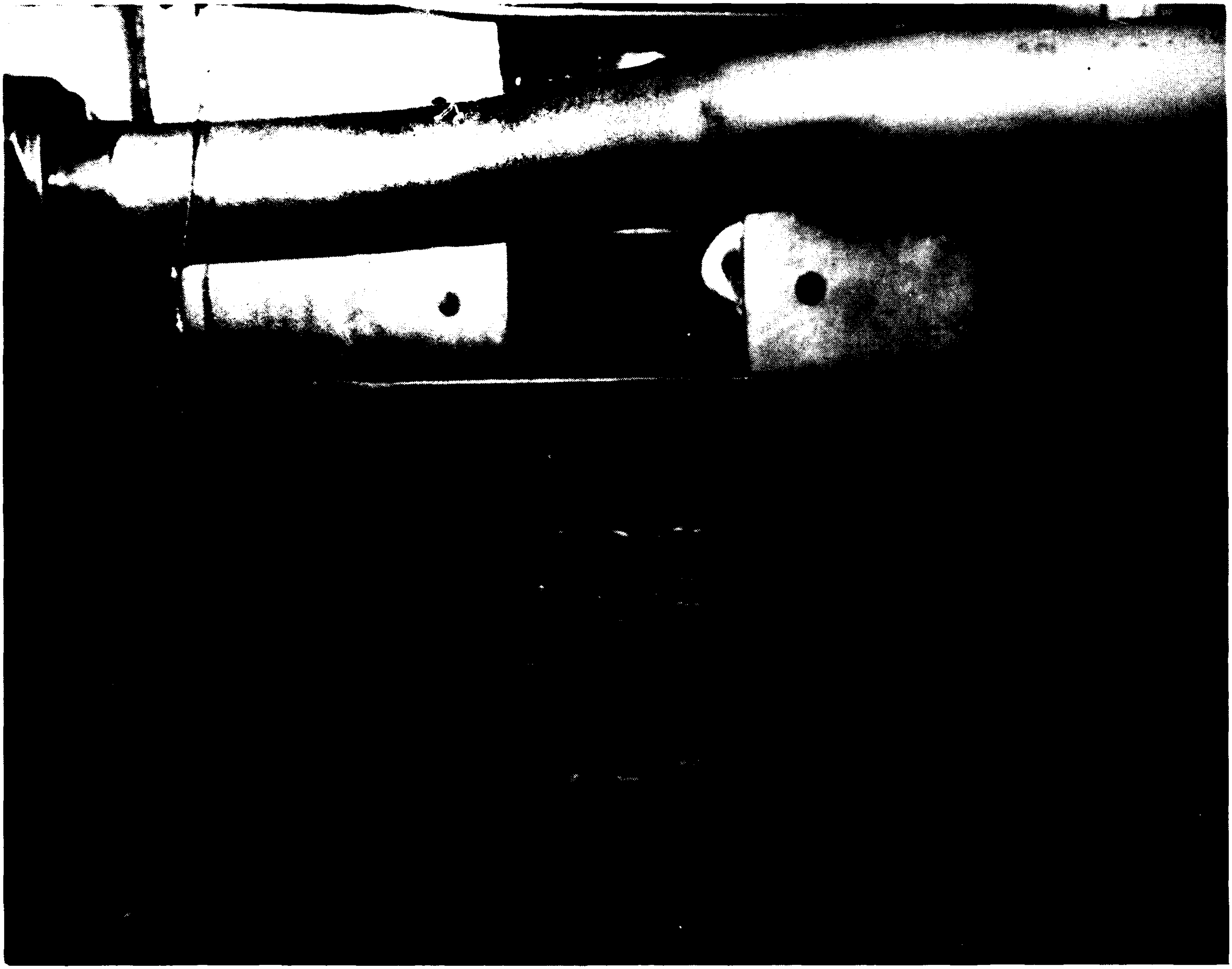


Figure 4–22. Photograph of Hold-Up in Simulator Tank Bottom, Run 8, LFP-14, 30% Hold-Up After Cavity Drain. Distance from Window Bottom to Tank Bottom = 3.5".

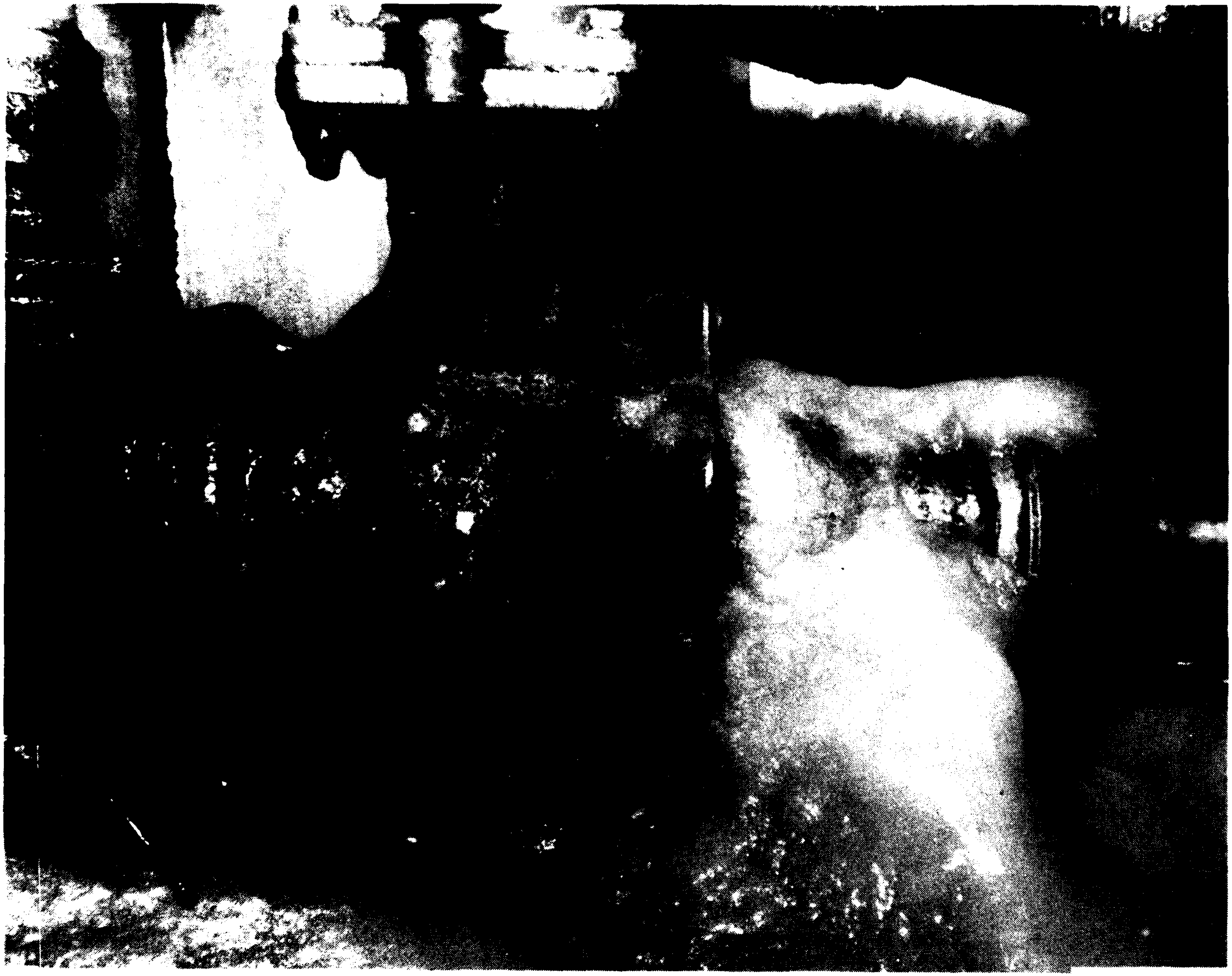


Figure 4–23. Photograph of Hold-Up in Vicinity of Boost Pump, Zero Tilt, Prior to Boost Pump Operation. Run No. 8

Figure 4–24. Photograph of Hold-Up in Vicinity of Boost Pump, Tank Tilted to Augment Gravity Drain. Prior to Boost Pump Operation. Run No. 8

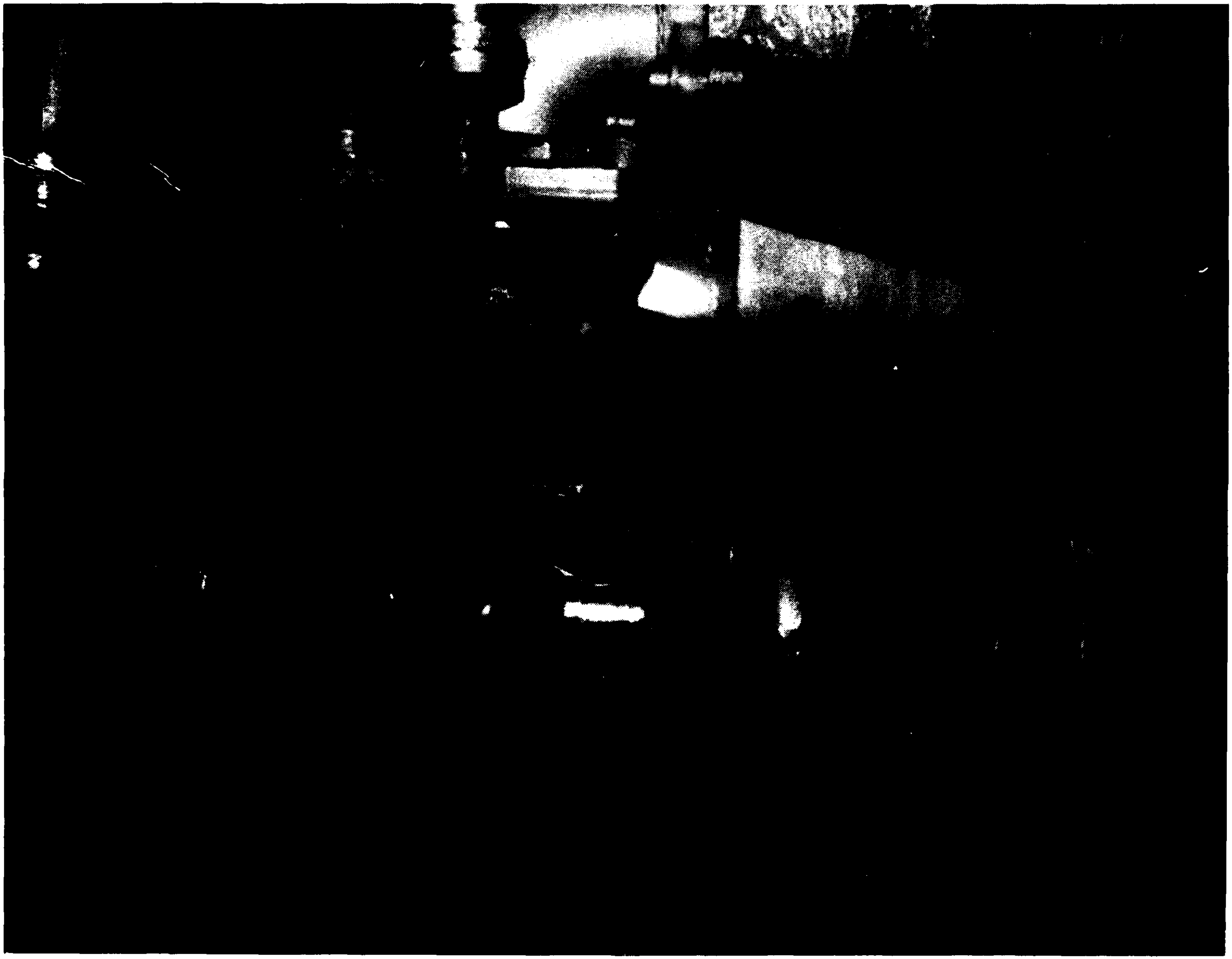


Figure 4–25. Photograph of Hold-Up in Vicinity of Boost Pump, Zero Attitude, One Minute Following Boost Pump Operation. Approximately 2% – 3% Liquid Fuel Removed During Pump Operation [illegible]

Figure 4–26. Photograph of Hold-Up in Simulator Tank, Run 8, LFP-14, 28% Hold-Up After Gravity Drain and After Boost Pump Operator

line. While no attempt was made to pump the slush while liquid fuel remained in the tank, slurry (liquid/solid) formations were observed to flow through the drain line (transparent plastic tubing) indicating some solid entrainment. Based on this observation, it is speculated that simultaneous bulk liquid flow would enhance the pumpability of the slu

The cavity shown in Figure 4-26 is a result of boost pump operation; during pump operation, considerable heat is released, which quickly melts any fuel in contact with pump metal parts. Figures 4-24 and 4-25 are sequential photographs taken before and after boost pump operation. Virtually no hold-up was observed on the vertical panel (baffle plate) located in the middle of the tank). Tests 4 and 8 were repeat tests at nominal test conditions with nearly identical results.

Observations of the formation and thawing of frozen fuel during alternating cooling and warming periods were not feasible with liquid fuel in the tank because of the opacity of the fuel at temperatures near the freeze point.

4.7 DISCUSSION

The results of this study show that the missions of each of the study aircraft could be successfully completed (i.e., with zero probability of operational interference) with the $-43^{o}C$ freeze point fuel. This conclusion is based on the result that zero hold-up was predicted or measured for the tracks studied. It is conceivable that more severe ground soak conditions than considered in this work could invalidate the above conclusion.

5.0 CONCLUSIONS

Generally, it was concluded that fuels with a freeze point substantially above that of JP-4 would permit normal flight operation.

5.1 POTENTIAL FUEL SPECIFICATION FREEZE POINT CHANGES

No hold-up was measured in any of the simulator tests with the JP8/LFP-1 test fuel, freeze point -43°C. This result indicates that the specification requirement for -58°C freeze point fuel is too restrictive. The Shell-Thornton data obtained for the JP-8/LFP1 mixture, Figure 4-2, suggests that the freeze point is approximately -46°C rather than the reported -43°C. On this basis the limited experimental data indicate that the requirement could be increased by at least 12°C and possibly as much as 15°C for the KC-135 and C-141 and by about 25°C for the B-52. These findings apply only to in-flight exposures; ground exposures could be more limiting.

5.2 POTENTIAL HOLD-UP LIMITS

Tne KC-135 and C-141 mission simulations produced excessive amounts of hold-up with the LFP-14 test fuel. Hold-up is considered excessive when a significant amount of fuel in the tank is trapped between stringers and not usable. It appears that up to 3% hold-up could be tolerated in the fuel tanks of the study aircraft since 97% of the fuel would still be usable; this would also provide assurance that the frozen material would not cause flow blockage in the boost pump.

6.0 RECOMMENDATIONS FOR FUTURE WORK

The following work is recommended for further research into the operational effects of the use of higher freeze point fuels:

- Improve the computer code to account for effects of frozen fuel and improve % hold-up predictions. The existing analytical model grossly overpredicts the % mass hold-up. A more realistic model would be desirable in order to arrive at valid conclusions with regards to the adverse effects of frozen fuels on aircraft performance. This will require representative data on specific heat, thermal conductivity and other fuel properties at temperatures below the freeze point.

- Improve visibility of fuel for observations of formation and thawing. Ultrasonic viewing techniques may be applicable if "cloudiness" is a fuel characteristic which cannot be improved. Ultrasonic viewing techniques are currently used in systems with opaque media (Ref. 4), however they are relatively expensive.

- Compare analytic and experimental data with airplane flight data. This step is required to give final verification of the analytical and experimental approach.

- Study drainability of cold fuel -- Is the solid/liquid mixture pumpable? What effect does drain line insulation have on the drainability? Answers to these questions would help determine the extent of frozen fuel allowable in a fuel tank.

- Extend analysis to include cylindrical tanks, $L \gg D$, representative of pylon and tip tanks. The current analytical model does not account for the two dimensional effects expected because of wall curvature.

- Perform measurements with several test fuels with $-40^{\circ}C$ freeze points. This step is desirable since commercial Jet A fuel has a $-40^{\circ}C$ freeze point and it would be of interest to know if Jet A fuel could be successfully used in military aircraft.

- o Evaluate ground temperature effects. Realistic ground soak periods and temperatures should be included to insure that the conclusions of this report as regards in-flight exposure are generally valid.

- o Evaluate other airplanes using procedures similar to those of this study. This extension of work would be relatively simple in view of the success of the analytical method of the present work.

- o Determine effects of fuel composition (i.e., paraffin content). It is known that certain additives can greatly alter the fuel freezing characteristics (Shell-Thornton curve). Such tests would provide insight into the basic behavior of fuels at low temperatures.

- o Determine margins of safety and make recommendations on operating procedures and specifications. Holdup formed in a fuel tank includes the separated wax and entrapped liquid. During thawing, the wax on cold surfaces could plug filters and lines and interrupt fuel flow to an engine. Flowability tests of cold fuel through typical filters and lines would provide insight into margins of safety involved with frozen fuel in the tanks.

7.0 REFERENCES

1. P. T. Ford and A. G. Robertson, "Jet Fuels - Redefining the Low Temperature Requirements," Shell Aviation News, No. 441, 22-26, (1977).

2. IP 217/66 Tentative Shell Thornton, J. of Inst. of Petroleum, V.48 (467) 388-390, November 1962.

3. G. N. Peterson, "Low Temperature Jet Fuel Study," Boeing Document D180-25483-1, September 1979.

4. N. C. Hoitink, et al, "Under Sodium Viewing Development for FFTF," Hanford Engineering Development Laboratory Report HEDL-SA-1922, 1980.

APPENDIX A

Track Data for 10 Northernmost Flights
B-52, C-141, and KC-135

The data presented show latitude/longitude/altitude and airspeed for the airplane along each of the tracks studied. A positive sign on latitude/longitude indicates north or east, while a negative sign indicates south or west.

All C-141 missions were planned for cruise at 39000 feet at Mach 0.74.

B-52 TRACKS

TRACK 1

LAT	LONG	FT	KTS
48	-101	35000	444
80	-110	35000	444
87	-130	35000	444
86	127	35000	444
75	120	35000	444
70	115	250	360
60	115	250	360
55	112	250	360
52	112	250	360
51	113	250	360
CIRCLE			
51	115	250	360
51	116	250	360
50	118	250	360
50	120	22000	444
38	127	0	0

TRACK 2

44	-103	35000	444
80	-70	35000	444
82	-30	35000	444
75	15	35000	444
72	15	35000	444
71	15	250	360
68	18	250	360
64	29	250	360
62	33	250	360
61	33	250	360
60	33	250	360
58	33	250	360
CIRCLE			
58	32	250	360
59	32	250	360
61	31	250	360
65	25	0	0

TRACK 3

48	-97	35000	444
80	-80	35000	444
81	-25	35000	444
78	18	35000	444
68	18	35000	444
68	18	250	360
63	20	250	360
63	29	250	360
61	33	250	360
61	35	250	360
58	35	250	360
58	39	250	360
57	40	250	360
CIRCLE			
57	38	250	360
57	37	250	360
56	36	250	360
56	25	250	360
61	35	250	360
63	29	250	360
65	25	0	0

TRACK 4

48	-97	35000	444
80	-100	35000	444
88	-120	35000	444
84	47	35000	444
78	47	35000	444
78	47	250	360
68	47	250	360
66	46	250	360
61	45	250	360
60	44	250	360
59	42	250	360
CIRCLE			
58	41	250	360
60	41	250	360
61	38	250	360
62	38	250	360
64	32	250	360
65	25	0	0

TRACK 5

48	-101	35000	444
80	-110	35000	444
88	-140	35000	444
86	80	35000	444
81	80	35000	444
80	80	250	360
75	80	250	360
65	75	250	360
60	70	250	360
55	64	250	360
51	66	250	360
CIRCLE			
51	61	250	360
51	60	250	360
50	60	22000	444
36	51	0	0

TRACK 6

46	-87	35000	444
80	-105	35000	444
87	-130	35000	444
85	80	35000	444
80	80	35000	444
80	80	250	360
75	80	250	360
65	75	250	360
60	70	250	360
55	64	250	360
52	66	250	360
CIRCLE			
51	60	250	360
50	60	22000	444
36	51	0	0

TRACK 7

44	-103	35000	444
80	-115	35000	444
86	-140	35000	444
85	116	35000	444
80	116	250	360
70	116	250	360
57	106	250	360
56	101	250	360
CIRCLE			
54	103	250	360
53	104	250	360
52	106	250	360
50	108	250	360
50	109	22000	444
38	127	0	0

TRACK 8

44	-103	35000	444
80	-80	35000	444
85	-20	35000	444
84	57	35000	444
79	57	35000	444
78	57	250	360
75	59	250	360
66	59	250	360
63	59	250	360
61	56	250	360
60	56	250	360
58	60	250	360
CIRCLE			
59	53	250	360
61	50	250	360
62	48	250	360
62	41	250	360
63	28	0	0

TRACK 9

44	-103	35000	444
80	-70	35000	444
85	-5	35000	444
84	43	35000	444
79	43	35000	444
73	44	35000	444
72	44	250	360
70	45	250	360
66	46	250	360
63	46	250	360
60	45	250	360
CIRCLE			
56	43	250	360
57	42	250	360
58	40	250	360
58	38	250	360
60	34	250	360
60	32	250	360
62	31	250	360
63	28	35000	444

TRACK 10

46	-87	35000	444
80	-75	35000	444
80	0	35000	444
68	13	35000	444
58	14	35000	444
58	15	250	360
56	20	250	360
55	23	250	360
CIRCLE			
55	25	250	360
54	25	250	360
53	21	250	360
56	13	0	0

C-141 TRACKS

ALTITTUDE: 39000 FT.   MACH NO. 0.74

Track 1

REQ MACKBLV 25 MAR 1977Z180242

843A PAED RJTY NOPAC NORTH H 25 DEC 80
PAEDAW 22AFOC-1 22AFOC-3

LN	COORDINATES	NAME	ALCON	ZD	TD	TC	VAR	CAI
0	6115N14948W	ELMENDORF						
1	6109N15012W	ANCHORAGE VOR		13	13	243	-25	
2	6047N16149W	BETHEL	+	339	352	266	-22	
3	6027N16424W	DEWIZ		79	431	255	-17	
4	5940N17000W	MATHY		174	605	254	-15	PA1
5	5727N18000W	BERIN		340	945	247	-10	PA1
6	5330N17000E	ABM ZOBRA		414	1359	235	-3	EA4
7	5200N16000E	TOYAN		426	1785	242	2	BA4
8	4941N15920E	PAZA/RJTG		32	1817	23[illegible]	4	
9	4400N15000E	ZAPOK		512	2329	228	6	BT1
10	4015N14500E	NOHO		316	2645	225	7	
11	3854N14314E	SPIKE/SPK		115	2760	225	7	
12	3709N14059E	IWAKI	+	149	2909	225	7	
13	3644N14021E	DAIGO VOR		39	2948	231	7	
14	3629N13952E	NIKKO NDB		28	2976	237	7	
15	3535N13923E	ZAMA NDB		59	3035	203	6	
16	3545N13921E	YOKOTA	D	10	3045	352	6	

PREVIOUS TD WAS 3045

DATA CHECK CAUTION COMMENTS
* 2 LON10,
* 6 W/E,
* 16 TC100,

Track 2

REQ MACKBLV 25 MAR 1927Z180689

519Z KDOV EGUN YHO-59/50-KF H 04 MAR 81
KDOVAW 21AFOC-1

IN	COORDINATES		NAME	ALCON	ZD	TD	TC	VAR	CAI
0	3908N	7528W	DOVER						
1	3906N	7448W	SEA ISLE		31	31	094	10	
2	3954N	7332W	MANTA		76	107	051	11	
3	4048N	7228W	HTO 236013		73	180	042	12	
4	4051N	7204W	ACK 270/96		18	198	081	13	
5	4111N	7033W	INTJ62-79		72	270	074	14	
6	4143N	7013W	HYANNIS		35	305	025	15	
7	4257N	7008W	ALTER HDG		74	379	003	16	
8	4355N	6930W	SEAER		64	443	025	17	
9	4451N	6852W	BANGOR		62	505	026	18	
10	4646N	6806W	PRESQUE ISLE		119	624	016	20	
11	4709N	6754W	CZQM		24	648	020	21	
12	5014N	6616W	SEPT-ILES VOR		196	844	019	23	
13	5126N	6537W	WACO		76	920	019	26	
14	5334N	6406W	CHURCHILL FALL		139	1059	023	28	
15	5528N	6013W	HOPEDALE	+	177	1236	050	31	
16	5900N	5000W	5900N 5000W		393	1629	057	35	AB1
17	6100N	4000W	6100N 4000W		323	1952	068	35	AD2
18	6217N	3413W	BIRK/CZQX		182	2134	065	33	
19	6300N	3000W	ICELAND ADIZ		124	2258	070	31	
20	6326N	2656W	UNIFORM 120		87	2345	073	29	
21	6359N	2236W	KEFLAVIK		120	2465	074	27	
22	6324N	2017W	VM NDB		71	2536	120	24	
23	6258N	1844W	LIMA 120		49	2585	122	23	
24	6100N	1234W	BIRK/EGGX		210	2795	124	20	
25	6000N	1000W	EGGX/EGPX		97	2892	126	16	
26	5813N	0611W	STORNOWAY	+	159	3051	132	14	
27	5502N	0143W	NEW/EGPX/EGTT		241	3292	142	10	
28	5342N	0006W	OTTRINGHAM		98	3390	145	8	
29	5305N	0010W	CONINGSBY TAC		37	3427	134	8	
30	5222N	0029E	MILDENHALL		49	3476	151	7	

PREVIOUS TD WAS 3476

DATA CHECK CAUTION COMMENTS
* 16 LCN10,
* 30 W/E,

Track 3

REQ MACKBLV 25 MAR 1927Z1E0928

419X PGSF PAID 73/70YRB E H 06 NOV 80

BGSFAW

LN	COORDINATES	NAME	ALCON	ZD	TD	TC	VAR	CAL
0	6701N 5043W	SONDRESTROM	+					
1	6657N 5128W	20DME		18	18	257	46	
2	6915N 5332W	GODHAVN RBN		146	164	342	48	
3	7100N 6000W	7100N 6000W		168	332	309	54	AH1
4	7240N 6750W	BGSF/CYEG		177	509	304	61	
5	7300N 7000W	7300N 7000W		43	552	298	66	BU1
6	7340N 7600W	ARCTIC CONTROL		111	663	291	70	
7	7400N 8000W	7400N 8000W		70	733	287	74	
8	7440N 9000W	7440N 9000W		167	900	284	79	BU1
9	7444N 9455W	RESOLUTE VOR		78	978	273	78	
10	7445N 9500W	21/22AF		2	980	299	76	
11	7445N10000W	7445N 10000W		79	1059	270	21	BU1
12	7433N11000W	7433N 11000W		159	1218	266	-60	
13	7304N12000W	7304N 12000W		189	1407	242	-57	BU8
14	7200N12540W	CZEG		120	1527	238	-50	
15	7100N13000W	DEWIZ		102	1629	234	-46	BU8
16	6644N14120W	CZEG/PAZA		349	1978	222	-38	
17	6448N14801W	FAIRBANKS	+	208	2186	236	-31	
18	6109N15012W	ANCHORAGE VOR	D	227	2413	195	-26	
19	6115N14948W	ELMENDORF	D	13	2426	063	-25	

PREVIOUS TD WAS 2426

DATA CHECK CAUTION COMMENTS

* 16 LON10,

* 19 TC100,

* NO RELAY CODE IN THIS TRK

Track 4

REQ MACKBLV 25 MAR 1927Z181000

536C KWRI BGTL FROBISHER O H 04 MAR 81
KWRIAW 21AFOC-1

LN	COORDINATES		NAME	ALCON	ZD	TD	TC	VAR	CAL
0	4001N	7436W	MCGUIRE						
1	3954N	7332W	MANTA		50	50	098	11	
2	4055N	7219W	HAMPTON		83	133	042	13	
3	4143N	7126W	PROVIDENCE		62	195	040	14	
4	4221N	7100W	BOSTON		43	238	027	15	
5	4326N	7037W	KENNEBUNK		67	305	015	16	
6	4646N	6806W	PRESQUE ISLE		227	532	028	18	
7	4719N	6811W	CZOM		33	565	354	21	
8	4832N	6822W	MONT JOLI		73	638	354	22	
9	4908N	6813W	BAIE-COMEAU		36	674	009	22	
10	5258N	6651W	WABUSH VOR		236	910	013	25	
11	5449N	6645W	SCHEFF-VIL VOR		111	1021	002	29	
12	5806N	6826W	FORT CHIMO VOR		205	1226	344	32	
13	6344N	6828W	FROBISHER VOR		338	1564	360	39	
14	6500N	6830W	CZEG/CZQM		76	1640	359	46	
15	6728N	6833W	DEWIZ		148	1788	359	50	
16	7028N	6835W	CLYDE RIVER		180	1968	360	57	
17	7100N	6836W	DEWIZ		32	2000	358	61	
18	7246N	6840W	JULET		106	2106	359	64	BU1
19	7300N	6839W	BIRD/CZEG		14	2120	357	66	
20	7450N	6834W	JULIETT 1		110	2233	001	69	
21	7632N	6842W	THULE AB		102	2332	359	73	

PREVIOUS TD WAS 2332

Track 5

REQ MACKBLV 25 MAR 1927Z181432

419A BGSF BGTL ALFA O H 13 AUG 79
BGSFAW 21AFOC-1

LN	COORDINATES		NAME	ALCON	ZD	TD	TC	VAR	CAL
0	6701N	5043W	SONDRESTROM	+					
1	6657N	5128W	20DME		18	18	257	46	
2	6915N	5332W	GODHAVN RBN		146	164	342	48	
3	7248N	5609W	UPERNAVIK NDB		219	383	347	54	
4	7344N	5835W	ALFA		70	453	323	59	
5	7521N	6340W	ALFA 1		126	579	320	64	
6	7632N	6842W	THULE AB	+	102	681	314	71	

PREVIOUS TD WAS 681

DATA CHECK CAUTION COMMENTS
* NO CAL FOR THIS TRK

Track 6

REQ MACKBLV 25 MAR 1927Z181442

839D PAEI PASY NOPAC NORTH H 25 DEC 80
PAEIAW 22AFOC-1

IN	COORDINATES	NAME	ALCON	ZD	TD	TC	VAR	CAL
0	6440N14706W	EIELSON						
1	6448N14801W	FAIRBANKS		25	25	289	-28	
2	6257N15537W	MCGRATH		229	254	241	-25	
3	6047N16149W	BETHEL	+	218	472	233	-20	
4	6027N16424W	DEWIZ		79	551	255	-17	
5	5940N17000W	MATHY		174	725	254	-15	BA1
6	5727N18000W	BERIN		340	1065	247	-10	BA1
7	5530N17600E	5530N 17600E		177	1242	229	-5	
8	5240N17502E	ROLEN IAF		173	1415	191	-4	
9	5243N17407E	SHEMYA AFB	+	33	1448	275	-3	

PREVIOUS TD WAS 1448

DATA CHECK CAUTION COMMENTS
* 7 W/E.

Track 7

REQ MACKBLV 25 MAR 1951Z190444

421B CYYR BGTL FROBISHER 0 H 04 MAR 81
CYYRAW 21AFOC-1

IN	COORDINATES	NAME	ALCON	ZD	TD	TC	VAR	CAL
0	5319N 6026W	GOOSE						
1	5334N 6406W	CHURCHILL FALL	D	132	132	277	30	
2	5449N 6645W	SCHEFF-VIL VOR	D	119	251	309	30	
3	5806N 6826W	FORT CHIMO VOR		205	456	344	32	
4	6344N 6828W	FROBISHER VOR		338	794	360	39	
5	6500N 6830W	CZEG/CZQM		76	870	359	46	AH1
6	6728N 6833W	DEWIZ		148	1018	359	50	
7	7028N 6835W	CLYDE RIVER		180	1198	360	57	
8	7246N 6840W	JULET		138	1336	359	63	BU1
9	7300N 6839W	BIRD/CZEG		14	1350	357	66	
10	7450N 6834W	JULIETT 1		110	1460	001	69	
11	7632N 6842W	THULE AB		102	1562	359	73	

PREVIOUS TD WAS 1562

Track 8

REO MACKBLV 25 MAR 1952Z191238

857D PAED EDAF G/C GRID H 25 MAR 81
PAEDAW 22AFOC-1 21AFOC-1

LN	COORDINATES	NAME	ALCON	ZD	TD	TC	VAR	CAL
0	6115N14948W	ELMENDORF						
1	6134N14958W	BIG LAKE		20	20	346	-25	
2	6448N14801W	FAIRBANKS		201	221	015	-27	
3	6634N14516W	FORT YUKON	+	126	347	033	-29	
4	6913N14100W	CZEG		186	533	031	-33	
5	6936N14011W	KOMAKUK NDB		29	562	037	-36	
6	7430N13000W	7430N 13000W		348	910	032	-42	BU1
7	7830N11000W	7830N 11000W		366	1276	048	-65	
8	8000N 8000W	8000N 8000W		343	1619	074	127	BU1
9	8000N 6920W	BIRK(BGSF)CYEG		111	1730	090	90	
10	7715N 4000W	7715N 4000W		379	2109	117	64	AE2
11	7500N 3000W	7500N 3000W		197	2306	133	44	
12	7100N 2000W	BGSF(LOW)/BIRK		296	2602	144	33	AD1
13	6900N 1625W	ADIZ		141	2743	149	26	
14	6500N 1130W	6500N 1130W		266	3009	155	21	AD4
15	6100N 0800W	BIRK/EGPX		258	3267	158	16	
16	5813N 0611W	STORNOWAY	+	176	3443	162	13	
17	5502N 0143W	NEW/EGPX/EGTT	M 250	241	3684	142	10	
18	5339N 0130E	DOGGER		140	3824	126	8	
19	5310N 0300E	BLUEBELL		61	3885	118	6	
20	5305N 0317E	BLF/EGTTEHAM	M 250	11	3896	116	6	
21	5220N 0506E	PAMPUS	M 250	80	3976	124	5	
22	5157N 0639E	ABM REKKEN		62	4038	112	5	
23	5155N 0647E	EDDY/EHAA		5	4043	112	4	
24	5143N 0735E	DORTMUND		32	4075	112	4	
25	5104N 0758E	EDDU-F/EDDY-L		42	4117	160	4	
26	5027N 0821E	LIMBURG		40	4157	159	3	
27	5025N 0915E	GEDERN		34	4191	093	3	
28	5017N 0851E	METRO	D	17	[illegible]208	242	3	
29	5002N 0834E	FRANKFURT MAIN	D	19	4227	216	3	

PREVIOUS TD WAS 4227

DATA CHECK CAUTION COMMENTS

* 6 LON10,
* 7 LON10,
* 8 LON10,
* 9 LON10,
* 10 LON10,
* 18 W/E,
* 28 TC100,

Track 9

```
REQ  MACEBLV     25 MAR 1952Z191553

863F   KTCM PAEI  COAST AWYS       L              14 NOV 80
KTCMAW 22AFOC-1
LN COORDINATES       NAME         ALCON   ZD    TD   TC  VAR CAL
 0 4709N12229W MCCHORD
 1 4726N12219W SEATTLE                    18    18 022 -22
 2 4823N12310W DISCO                      66    84 329 -22
 3 4844N12329W VICTORIA VOR               24   108 329 -22
 4 4945N12457W COMOX NDB                  84   192 317 -23
 5 5041N12722W PORT HARDY                108   300 301 -24
 6 5303N12941W ETHELDA                   166   466 329 -25
 7 5406N13038W WACAL                      72   538 332 -26
 8 5443N13114W CZVR/PAZA                  43   581 330 -27
 9 5504N13135W ANNETTE IS                 24   605 330 -27
10 5652N13533W BIORKA IS      M 100 171   776 309 -28
11 5931N13939W YAKUTAT        M 100 205   981 321 -28
12 6029N14636W JOHNSTONE PT   M 100 216  1197 286 -28
13 6209N14527W GULKANA        M 100 105  1302 018 -27
14 6400N14543W BIG DELTA      M 120 111  1413 356 -28
15 6440N14706W EIELSON                54 1467 318 -29
                         PREVIOUS TD WAS 1467

DATA CHECK CAUTION COMMENTS
          * NO CAL FOR THIS TRK
```

Track 10

REQ MACKBLV 25 MAR 1957Z191677

4?0M BGTL KDOV FROBISHER F H 04 MAR 81
BGTLAW 21AFOC-1

LN	COORDINATES		NAME	ALCON	ZD	TD	TC	VAR	CAL
0	7632N	6842W	THULE AB	+					
1	7450N	6834W	JULIETT 1		102	102	179	73	
2	7300N	6839W	BIRD/CZEG		110	212	181	69	
3	7246N	6840W	JULET		14	226	177	66	BU1
4	7100N	6836W	DEWIZ		106	332	179	64	
5	7028N	6835W	CLYDE RIVER	+	32	364	179	61	
6	6500N	6830W	CZEG/CZQM		328	692	180	54	
7	6344N	6828W	FROBISHER VOR		76	768	179	46	AK2
8	5806N	6826W	FORT CHIMO VOR		338	1106	180	39	
9	5400N	7035W	CADIZ		256	1362	196	30	
10	5312N	7055W	NITCHEQUON		49	1411	194	26	
11	5200N	7208W	CZQM/CZUL		85	1496	212	24	
12	4948N	7430W	CHIBOUGAMA RBN		159	1655	214	20	
13	4553N	7423W	MIRABEL		235	1890	179	16	
14	4503N	7412W	CZUL		54	1944	177	14	
15	4245N	7348W	ALBANY		136	2080	173	14	
16	4146N	7336W	PAWLING		60	2140	171	13	
17	4056N	7248W	CALVERTON		62	2202	144	13	
18	4031N	7248W	SARDI		25	2227	180	13	
19	3954N	7332W	MANTA		50	2277	222	12	
20	3906N	7448W	SEA ISLE		76	2353	231	11	
21	3908N	7528W	DOVER		31	2384	274	10	

PREVIOUS TD WAS 2384

KC-135 TRACKS

TRACK 1

LAT	LONG.	ALT.(FT).	KTS
48.0	-101.0	35000.0	444.0
75.6	-106.6	35000.0	444.0
78.1	-108.0	35000.0	444.0
75.6	-106.0	35000.0	444.0
48.0	-101.0	0	0

TRACK 2

LAT	LONG.	ALT.(FT).	KTS
44.0	-103.0	35000.0	444.0
57.7	- 99.0	35000.0	444.0
60.2	- 98.0	35000.0	444.0
57.7	- 99.0	35000.0	444.0
44.0	-103.0	0	0

TRACK 3

LAT	LONG.	ALT.(FT).	KTS
48.0	- 97.0	35000.0	444.0
74.9	- 80.0	35000.0	444.0
77.4	- 82.0	35000.0	444.0
74.9	- 80.0	35000.0	444.0
48.0	- 97.0	0	0

TRACK 4

LAT	LONG.	ALT.(FT).	KTS
48.0	- 97.0	35000.0	444.0
75.2	- 98.9	35000.0	444.0
77.7	- 99.0	35000.0	444.0
75.2	- 98.9	35000.0	444.0
48.0	- 97.0	0	0

NOTE: All latitudes (LAT) are North of Equator. Minus longitudes (LONG) are West, and positive are East

TRACK 5

LAT	LONG.	ALT.(FT).	KTS
48.0	-101.0	35000.0	444.0
80.0	-110.0	35000.0	444.0
88.1	-141.0	35000.0	444.0
89.4	- 48.0	35000.0	444.0
88.1	-141.0	35000.0	444.0
80.0	-110.0	35000.0	444.0
48.0	-101.0	0	0

TRACK 6

LAT	LONG.	ALT.(FT).	KTS
46.0	- 87.0	35000.0	444.0
80.0	-105.0	35000.0	444.0
87.0	-130.0	35000.0	444.0
89.5	-130.0	35000.0	444.0
87.0	-130.0	35000.0	444.0
80.0	-105.0	35000.0	444.0
46.0	- 87.0	0	0

TRACK 7

LAT	LONG.	ALT.(FT).	KTS
44.0	-103.0	35000.0	444.0
80.0	-115.0	35000.0	444.0
83.8	-124.5	35000.0	444.0
86.3	-140.0	35000.0	444.0
83.8	-124.5	35000.0	444.0
80.0	-115.0	35000.0	444.0
44.0	-103.0	0	0

AD-A121 688 FUEL/ENGINE/AIRFRAME TRADE-OFF STUDY OPERATIONAL EFFECTS OF INCREASED FRE..(U) BOEING MILITARY AIRPLANE CO SEATTLE WA P M MCCONNELL ET AL. AUG 82 2/2

UNCLASSIFIED AFWAL-TR-82-2067 F33615-78-C-2001 F/G 21/4 NL

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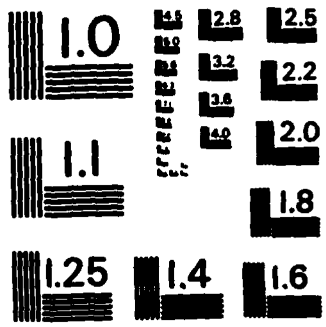

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS - 1963 - A

TRACK 8

LAT	LONG.	ALT.(FT).	KTS
44.0	-103.0	35000.0	444.0
80.0	- 80.0	35000.0	444.0
85.0	- 20.5	35000.0	444.0
85.6	24.2	35000.0	444.0
83.5	30.0	35000.0	444.0
85.0	- 20.0	35000.0	444.0
80.0	- 80.0	35000.0	444.0
44.0	-103.0	0	0

TRACK 9

LAT	LONG.	ALT.(FT).	KTS
44.0	-103.0	35000.0	444.0
70.7	- 90.7	35000.0	444.0
73.2	- 80.0	35000.0	444.0
70.7	- 90.7	35000.0	444.0
44.0	-103.0	0	0

TRACK 10

LAT	LONG.	ALT.(FT).	KTS
64.4	-147.0	35000.0	444.0
80.0	-155.7	35000.0	444.0
85.6	24.2	35000.0	444.0
83.5	30.0	35000.0	444.0
85.6	24.2	35000.0	444.0
80.0	-155.0	35000.0	444.0
64.4	-147.0	0	0

APPENDIX B

Fuel Usage Sequence

The fuel usage sequences in Tables B-1 through B-3 were extracted from USAF Technical Orders. They were used to calculate fuel tank ullage depth, fuel volume and wetted tank area vs time in Tables B-4 through B-7.

Table B-1

Typical B-52 Fuel Consumption Procedure

1	TAKEOFF		
	Aft Body	to Engines	1, 2
	No. 2 Main	to Engines	3, 4
	No. 3 Main	to Engines	5, 6
	Ctr Wing	to Engines	7, 8
2	CLIMB		
	Aft Body	to Engines	1, 2, 3, 4
	Ctr Wing	to Engines	5, 6, 7, 8
3	Aft Body	to Engines	1, 2, 3, 4
	Fwd Body	to Engines	5, 6, 7, 8
4	Mid Body	to All Engines	
5	Aft Body (Down to 13,000#)	to All Engines	
6	Aft Body	to Engines	1, 2, 7, 8
	No. 2 Main	to Engines	3, 4
	No. 3 Main	to Engines	5, 6
7	Main Tanks (To Green Band in Mains 1 & 4)	to All Engines	
8	L.H. External	to Engines	1, 2
	No. 2 Main	to Engines	3, 4
	No. 3 Main	to Engines	5, 6
	R.H. External	to Engines	7, 8
9	L.H. Outboard 5,000#	to Engines	1, 2
	No. 2 Main 5,000#	to Engines	3, 4
	No. 3 Main 5,000#	to Engines	5, 6
	R.H. Outboard 5,000#	to Engines	7, 8
10	L.H. Outboard	to Engines	1, 2, 3, 4
	R.H. Outboard	to Engines	5, 6, 7, 8
11	Main Tanks	to All Engines	

Table B-2.

C-141 FUEL USAGE SEQUENCE

The sequence for normal fuel usage is:

1. For take-off, use tank-to-engine feed from auxiliary tanks. Burn approximately 1,050 pounds per tank.

2. Use fuel equally from extended range tanks until empty.

3. Use fuel equally from auxiliary tanks until auxiliary tanks No. 2 and No. 3 are empty.

4. Use fuel equally from auxiliary tanks No. 1 and No. 4 and main tanks No. 2 and No. 3 until auxiliary tanks No. 1 and No. 4 are empty.

5. Use fuel equally from all main tanks.

Table B-3.

C-135 Fuel Management Sequence

❶ TOTAL RAMP FUEL							FUEL VALVE POSITIONS	FLIGHT CONDITION	FUEL QUANTITY AND TANK USE
UP to 50,000	50,000 to 72,000	72,000 to 99,500	99,500 to 109,500	109,500 to 119,500	119,500 to 136,000	136,000 or greater			
1	1	1	1	1	1	1	1, 3, & 4, Tank to Engine, #2 Tank to Manifold	START ENGINES, TAXI and TAKEOFF	Mains 1, 2, 3, and 4 ❷
			2	2	2	2	1, 2, 3 & 4 Tank to Manifold	ENROUTE CLIMB and CRUISE	10,000 lb from Center Wing
					3	3		CRUISE	10,000 lbs from Aft Body
						4			Start with Forward Body and use in ratio of 1 lb from Forward Body and 1-1/2 lb from Aft Body. Do not exceed 6700 lb from Forward Body or 10,000 lb from Aft Body. Use until empty. ❻
					4				Forward Body, use until empty ❻
			3	3	5				Aft Body, use until empty
2	2	2	4	4	6	5			Center Wing retain 10,000 lb until after final takeoff. This step may be deleted if the desired cg for takeoff can be maintained.
2A	2A	2A	4A	4A	6A	5A			Center Wing, use until empty ❸
	3	3	5	5	7	6			Use tanks 1 & 4 to all engines until quantities in 1 & 1R equal quantity in 2, and quantity in 4 & 4R equal quantity in 3
	4	4	6	6	8	7	1R & 4R Open	❹	Drain reserves 1 & 4
3	5	5	7	7	9	8	1, 3 & 4 Tank to Engine, #2 Tank to Manifold	LANDING ❺	Use until completion of mission

❶ *Determine ramp fuel aboard, select appropriate column, and follow indicated steps*

❷ Whenever the airplane gross weight is greater than the maximum brake release gross weight for takeoff, fuel must be used from a body tank during ground operation.

❸ *Sequence of this step dependent upon mission takeoff requirements*

❹ Do not accomplish at G.W. in excess of 240,000 lb for 1 ▶ 15 or 245,000 lb for 16 ▶ (2.5 g)
Do not accomplish at G.W. in excess of 268,000 lb for 1 ▶ 15 or 293,000 lb for 16 ▶ (2.0 g)

❺ For any TAKEOFF or LANDING with less than 10,500 lb in any main tank, all valves *Tank to Manifold* and all boost pumps ON

❻ Retaining some forward body fuel may be required for CG control.

Table B-4

Fuel Usage

	TANK DEPTH (IN)	TIME (HRS)	ULLAGE DEPTH (IN)	PERCENT OF TOTAL
B-52	18	0	0	0
	START OF WITHDRAWAL	14.6	0	0
		15.43	9.0	50.0
		15.65	17.0	94.4
C-141	19.5	0	0	0
	START OF WITHDRAWAL	8.73	0	0
		10.00	11.7	60.0
		11.90	18.5	94.9
KC-135	15.0	0	0	0
	START OF WITHDRAWAL	5.20	0	0
		5.48	14.0	93.3

Table B-5

B-52 Outboard Wing Tank Fuel Wetted Area vs Volume

INDEX	HEIGHT IN	FUEL VOLUME FT3	FUEL WETTED AREA FT2
1	-13.4159	0.0000	0.0000
2	-12.4159	.0180	.4980
3	-11.4159	.1266	1.5972
4	-10.4159	.3910	3.8786
5	-9.4159	.7895	6.3454
6	-8.4159	1.4361	9.1781
7	-7.4159	2.3016	12.3345
8	-6.4159	3.6506	16.3961
9	-5.4159	4.8221	20.1635
10	-4.4159	7.1237	24.5892
11	-3.4159	8.4830	29.0219
12	-2.4159	10.4402	33.4017
13	-1.4159	12.8616	37.7285
14	-.4159	15.9839	42.0023
15	.5841	18.7358	46.2232
16	1.5841	23.0911	59.3912
17	2.5841	25.4042	54.5062
18	3.5841	29.1339	58.5682
19	4.5841	32.9848	62.6098
20	5.5841	35.5852	67.0179
21	6.5841	42.5163	72.5061
22	7.5841	49.1289	78.5594
23	8.5841	58.7464	86.8969
24	9.5841	63.8271	96.0763
25	10.5841	68.8759	105.1263
26	11.5841	73.6539	114.0464
27	12.5841	79.7618	122.8368
28	13.5841	82.6463	131.4974
29	14.5841	86.8646	140.0282
30	15.5841	90.9005	148.4293
31	16.5841	94.1288	156.7007
32	17.5841	98.4324	164.8423
33	18.5841	105.5939	177.8732
34	19.5841	114.4816	182.6574
35	20.5841	120.7315	187.2479
36	21.5841	126.6624	191.7616
37	22.5841	132.2445	196.1986
38	23.5841	135.8431	200.5887
39	24.5841	142.2589	204.8421
40	25.5841	143.6543	209.0487
41	26.5841	145.8676	213.1785
42	27.5841	144.6548	217.2314
43	28.5841	147.7952	221.2076
44	29.5841	146.3205	225.1070
45	30.5841	140.8675	228.9296
46	31.5841	138.3708	233.9938
47	32.5841	134.5790	236.7270
48	33.3875	151.4525	236.7270

Table B-6

C-141 No. 1/4 Main Tank Fuel Wetted Area vs Volume

INDEX	HEIGHT IN	FUEL VOLUME FT3	FUEL WETTED AREA FT2
1	-11.5944	0.0000	0.0000
2	-10.5944	.0180	.6439
3	-9.5944	.1366	1.7682
4	-8.5944	.4423	4.5061
5	-7.5944	1.0380	6.9950
6	-6.5944	2.1186	12.1788
7	-5.5944	3.1081	17.0392
8	-4.5944	4.9080	24.5044
9	-3.5944	6.7778	30.1186
10	-2.5944	9.4045	38.7981
11	-1.5944	13.5171	46.6620
12	-.5944	16.9684	57.3258
13	.4056	22.3258	65.9677
14	1.4056	26.7261	77.1951
15	2.4056	34.1734	88.3062
16	3.4056	39.5205	99.2488
17	4.4056	42.8385	109.9991
18	5.4056	50.1839	120.6797
19	6.4056	59.2940	132.8629
20	7.4056	66.7965	145.3922
21	8.4056	82.4992	152.8836
22	9.4056	92.5469	157.1212
23	10.4056	108.7491	163.6957
24	11.4056	118.0267	169.0446
25	12.4056	133.7979	177.6531
26	13.4056	143.9960	187.8435
27	14.4056	158.2778	200.4778
28	15.4056	169.7493	217.7595
29	16.4056	173.4087	233.8858
30	17.4056	180.2337	254.5582
31	18.4056	183.5071	270.7436
32	19.4056	177.9962	276.1811
33	20.4056	167.4631	286.2912
34	21.4056	182.0032	293.3680
35	21.6612	188.8691	293.3680

Table B-7

KC-135 No. 1A Reserve Tank Fuel Wetted Area vs Volume

INDEX	HEIGHT IN	FUEL VOLUME FT3	FUEL WETTED AREA FT.
[illegible]	[illegible]	0.0000	0.00
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
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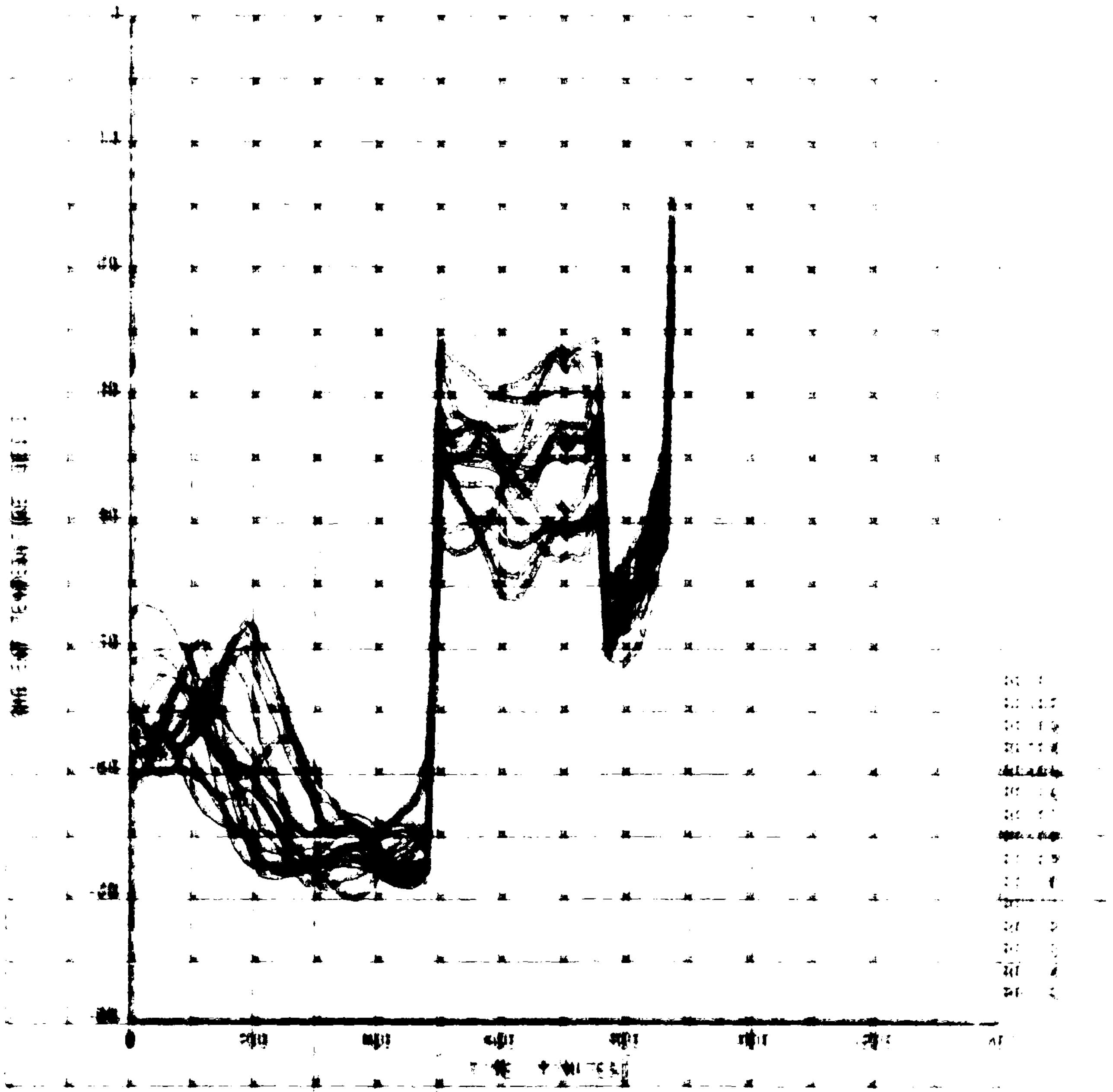
APPENDIX C

The fifteen worst case day ambient temperatures are plotted for each of ten (10) aircraft tracks. From the 15 worst days, the single worst day profile was selected and plotted for each track; plots of the calculated recovery temperature are included with the single worst day ambient temperatures.



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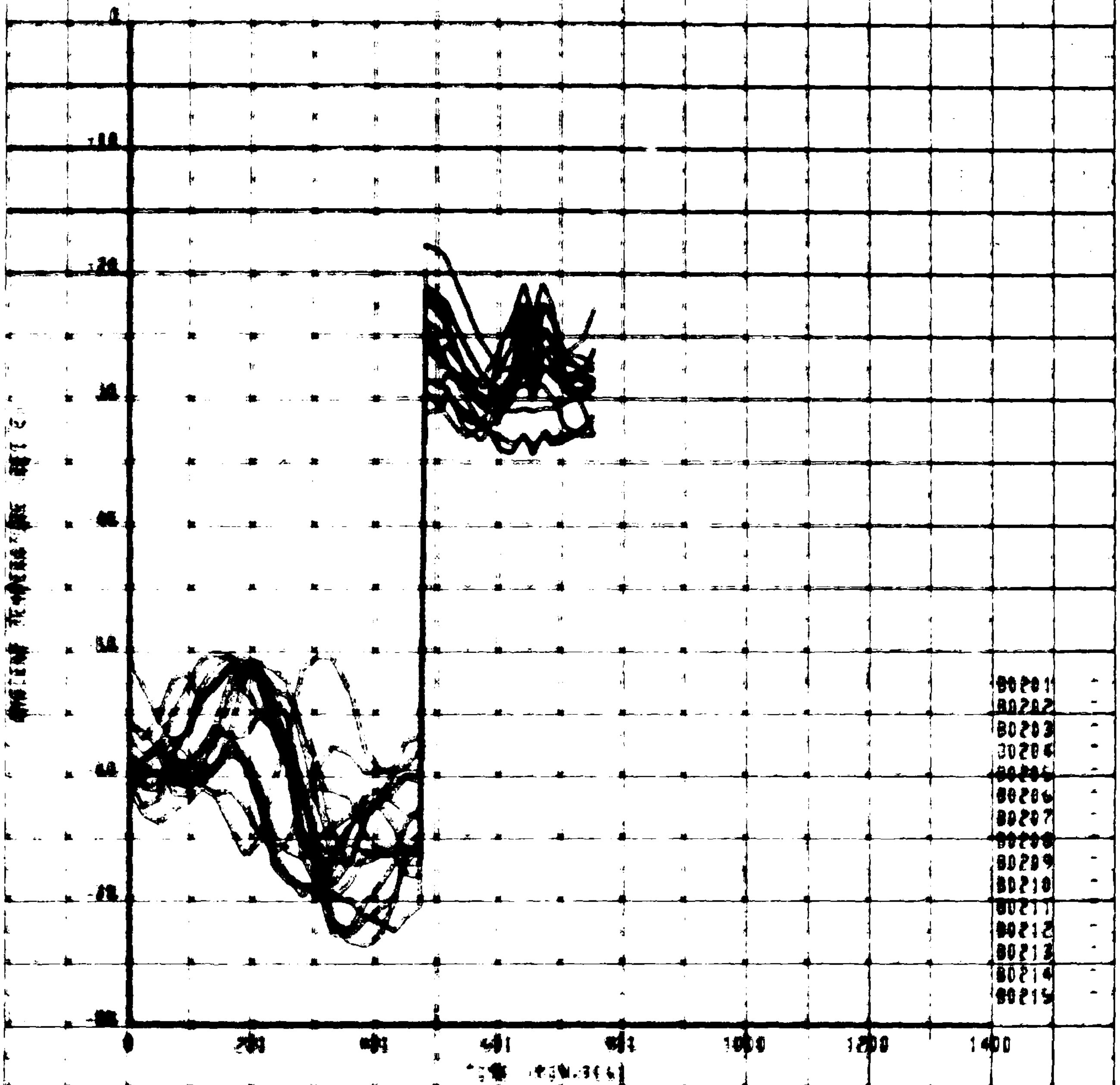
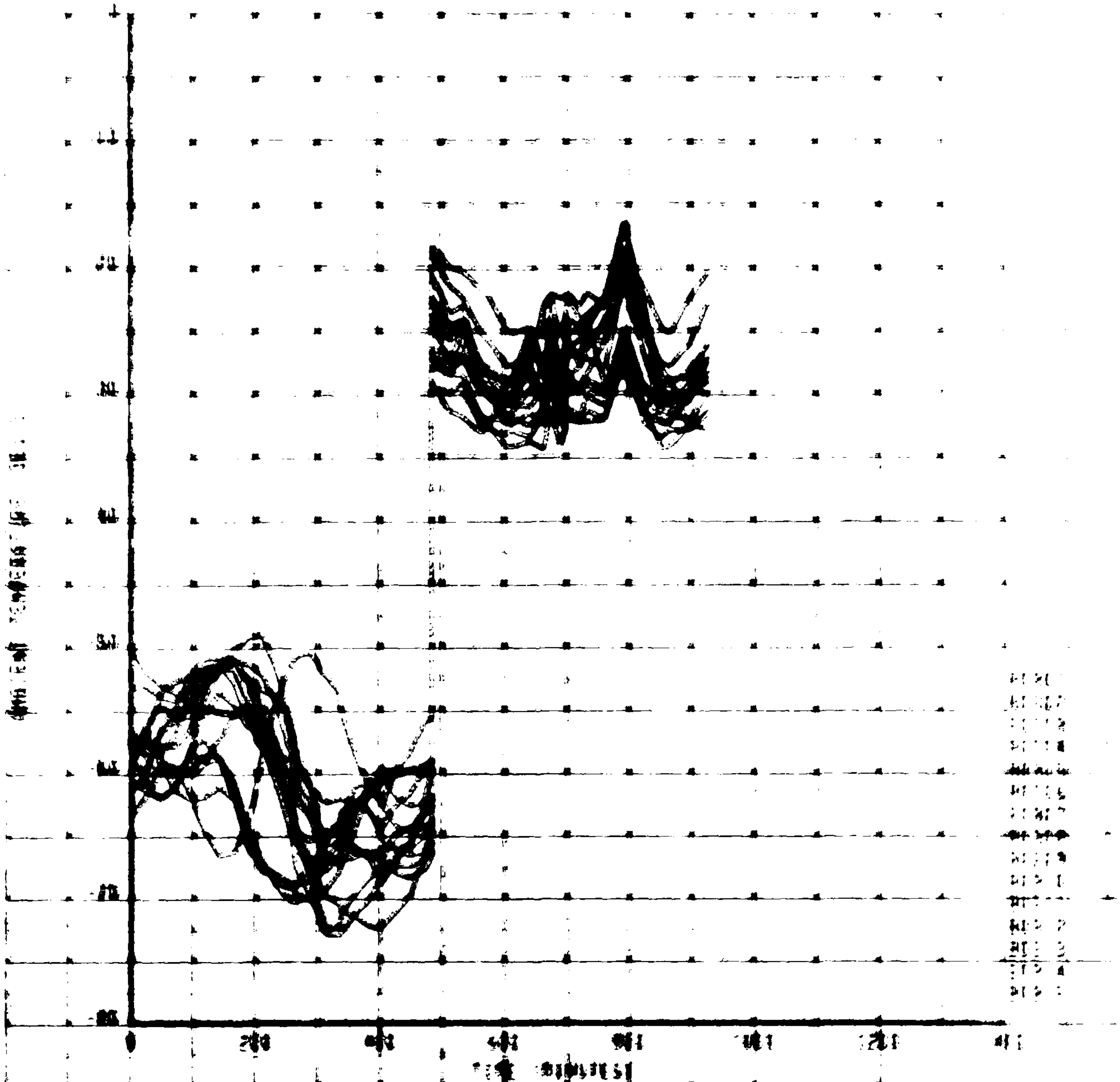


		B-52 DATA	Figure C-2
			PAGE C-3



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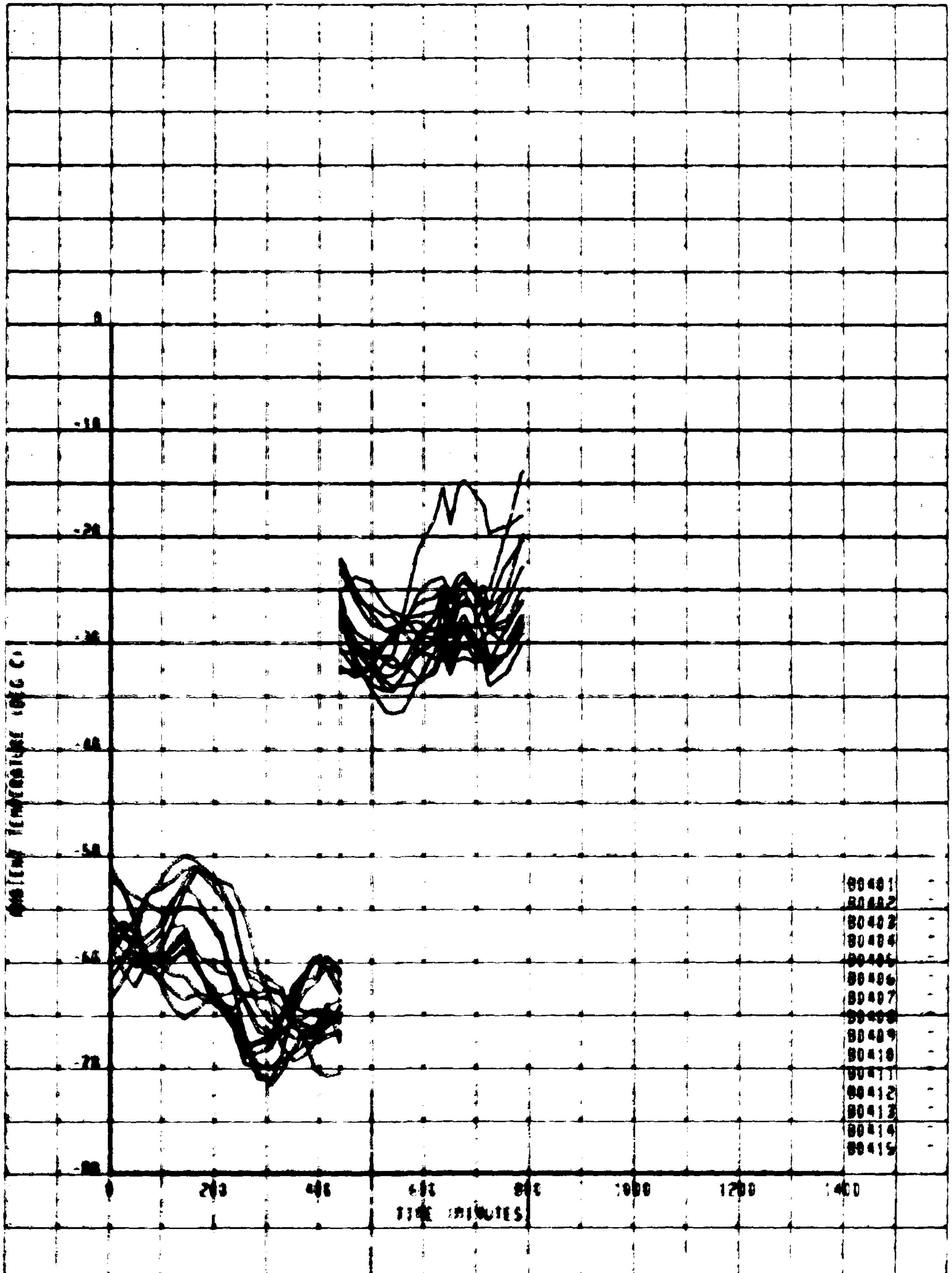
WORST CASE COLD DAYS

THE BOEING COMPANY

Figure C-?



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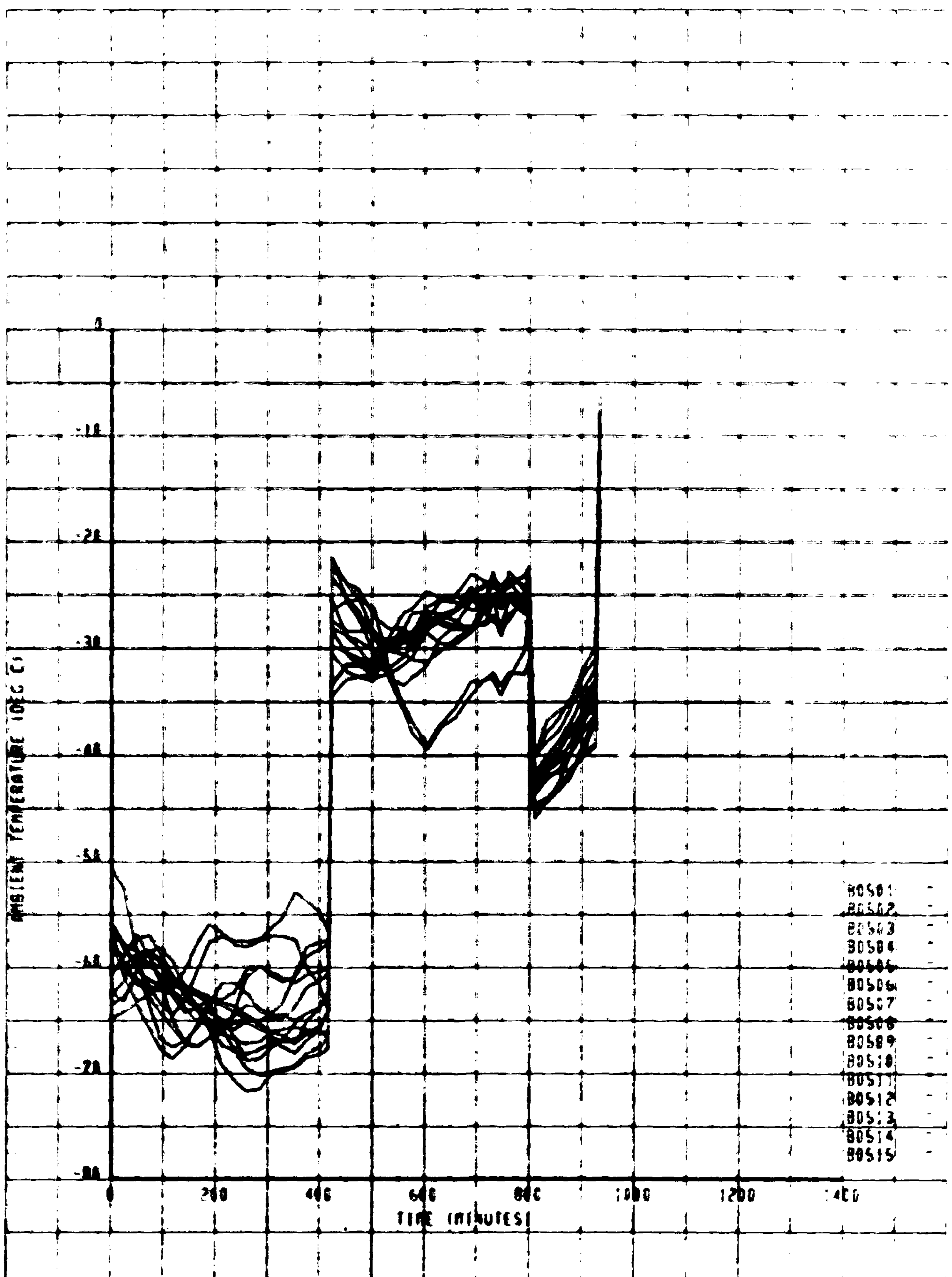

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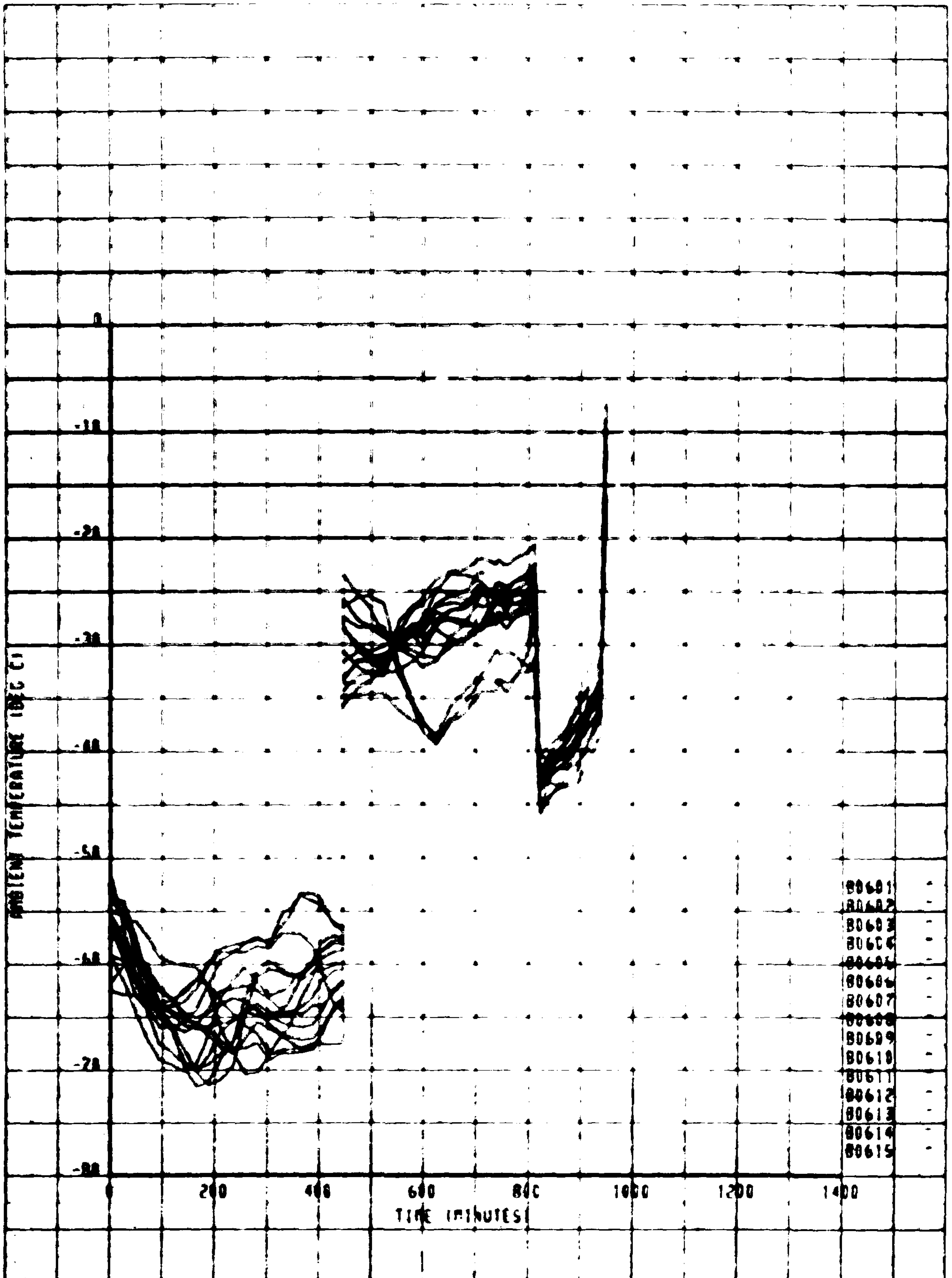

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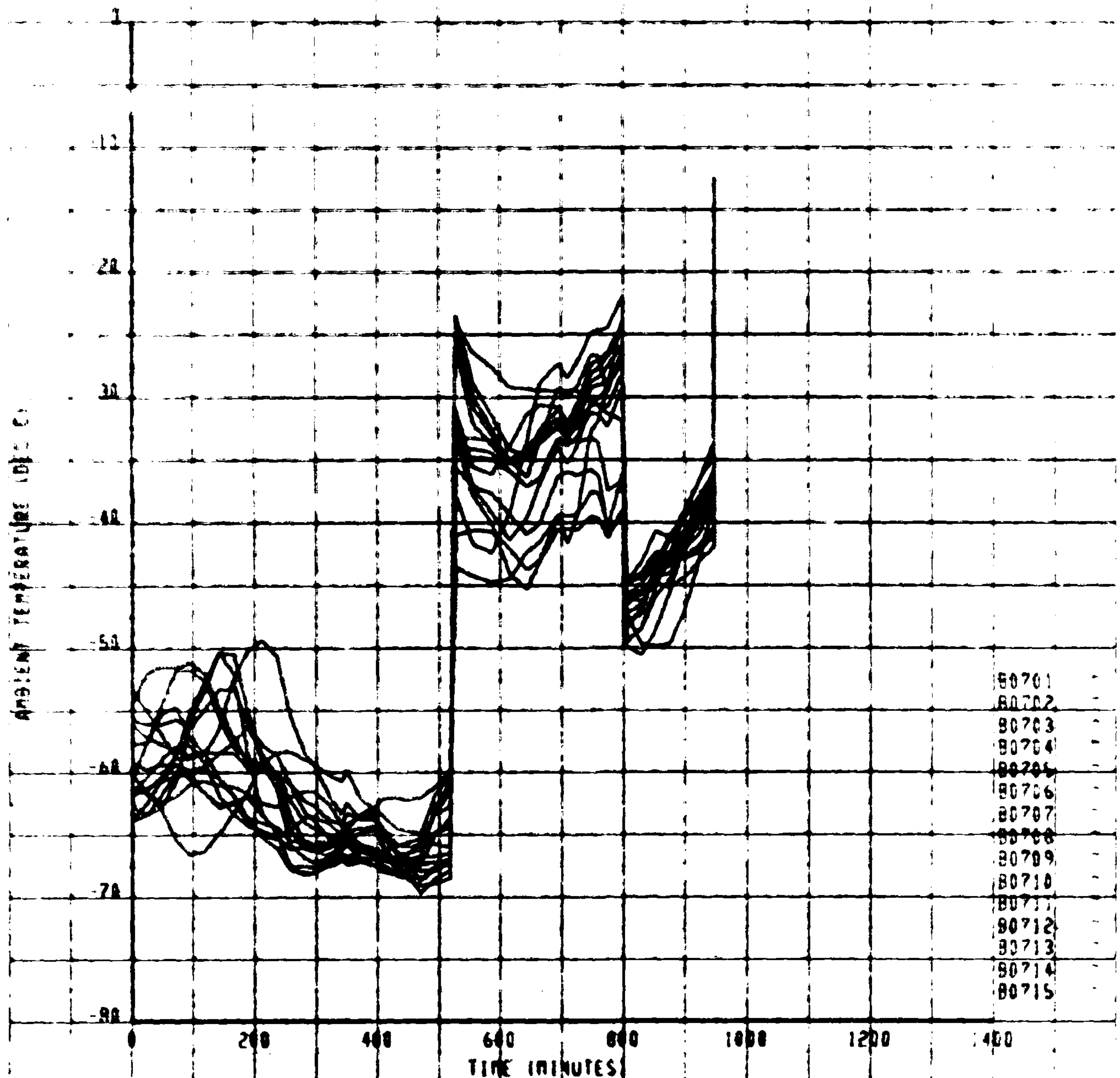

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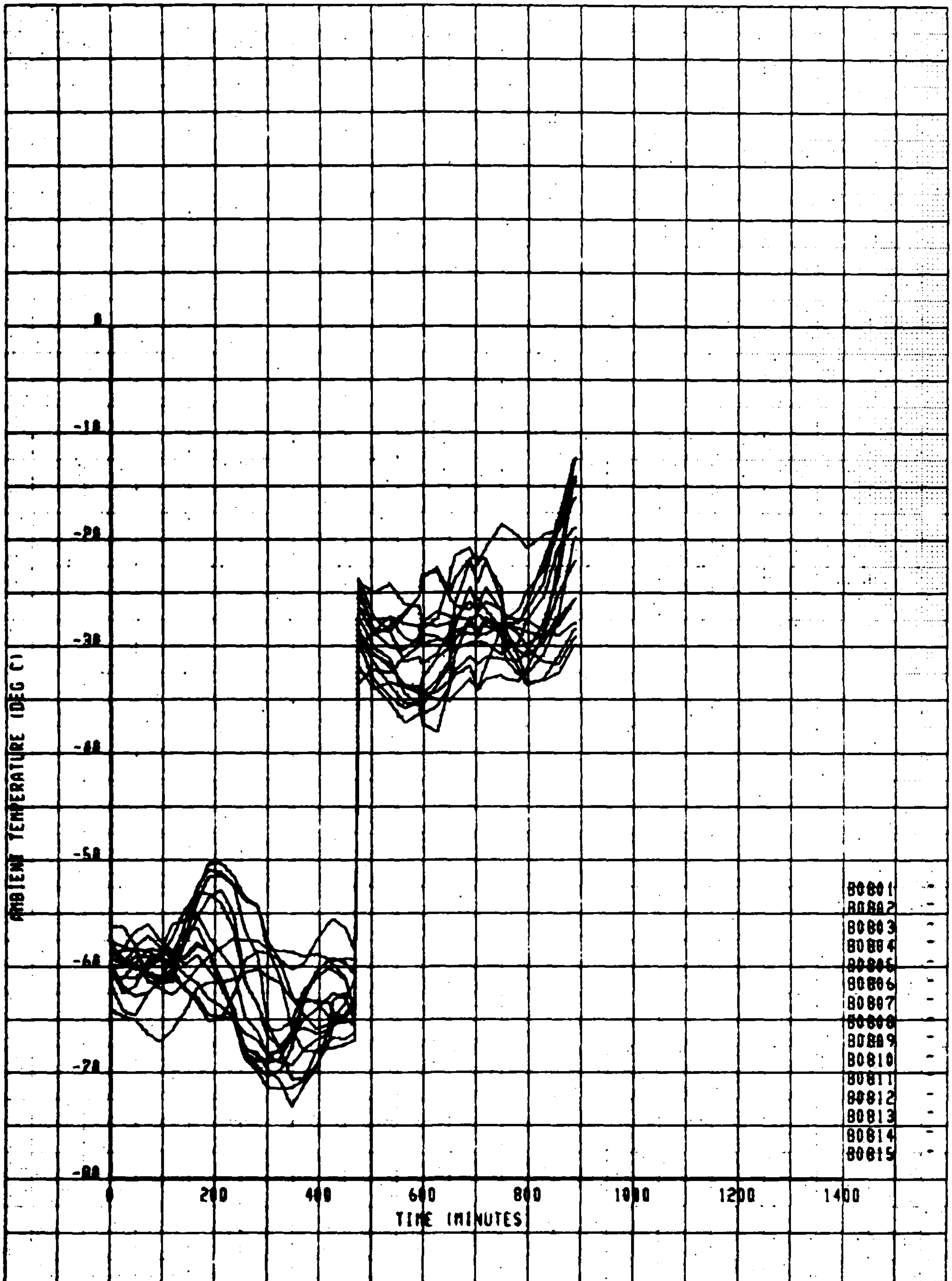

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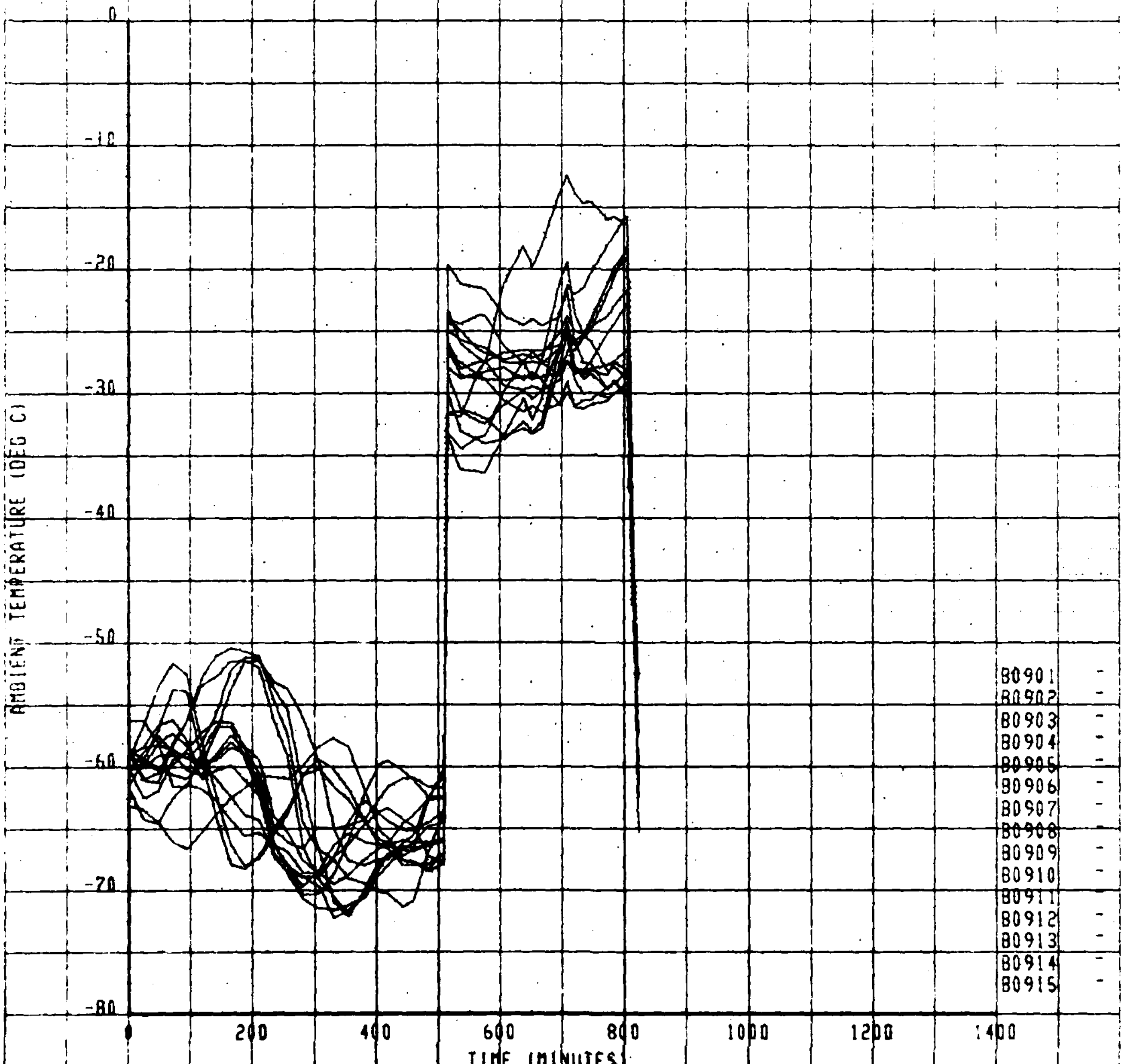

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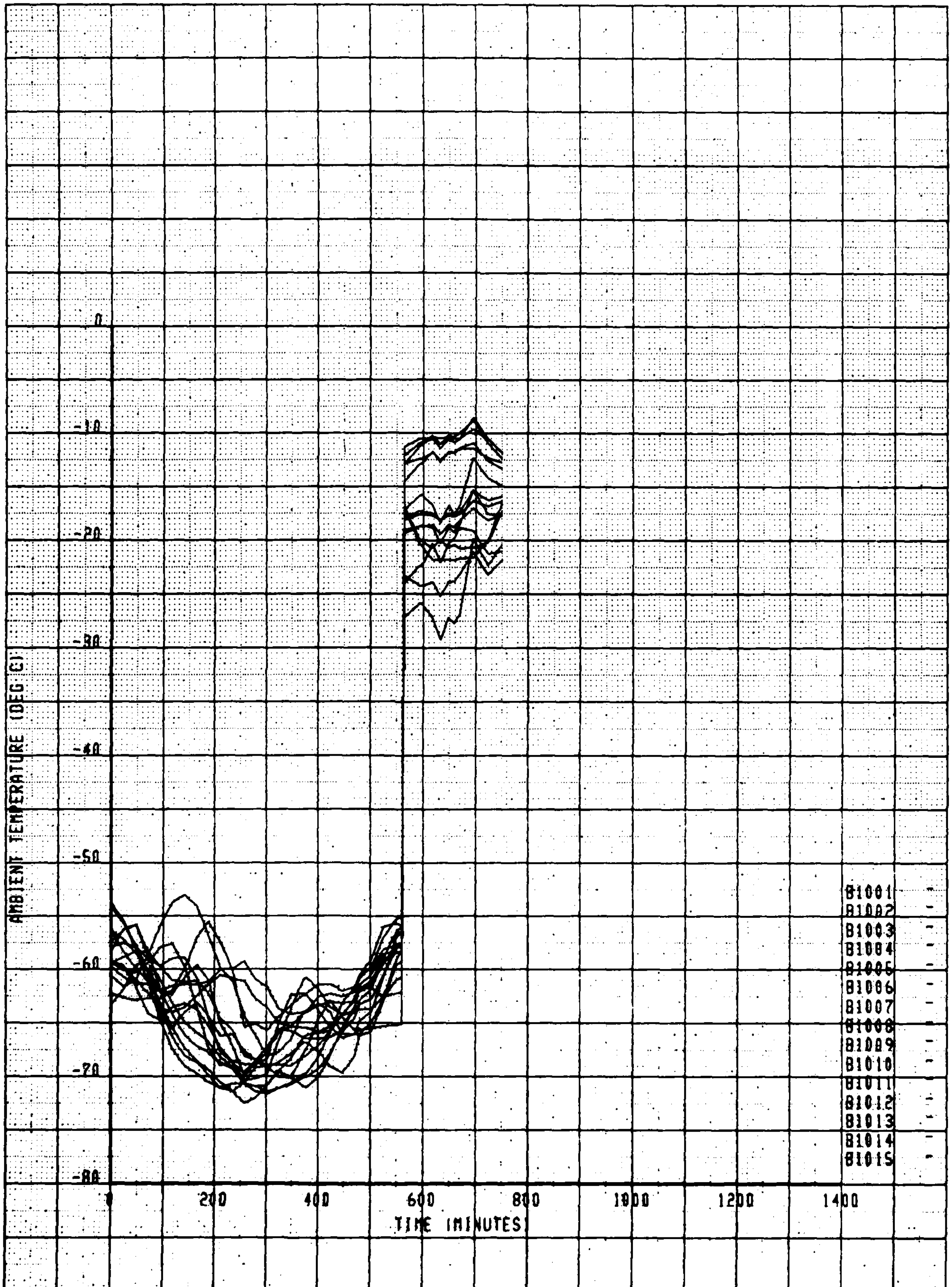

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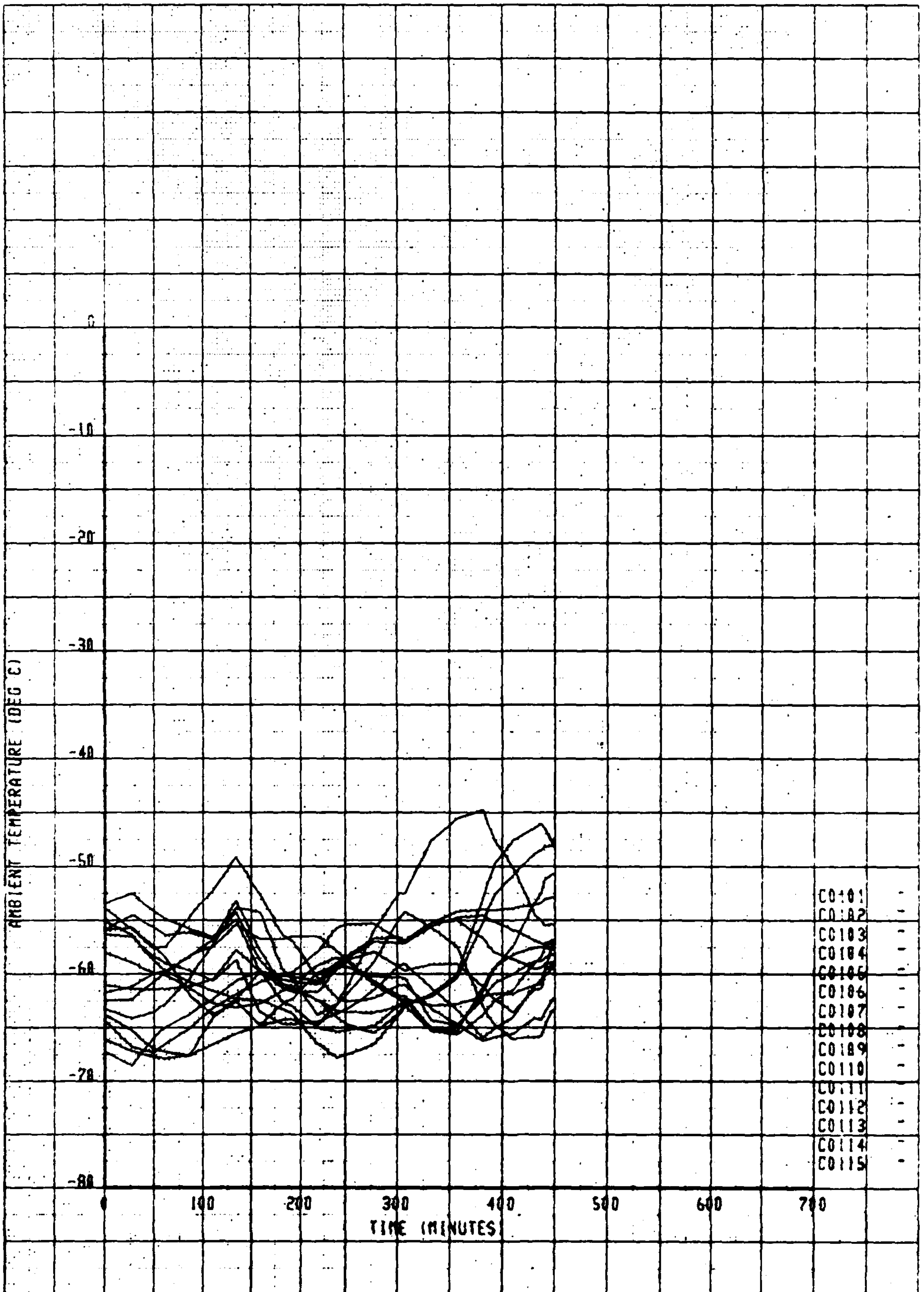

C141 TT2

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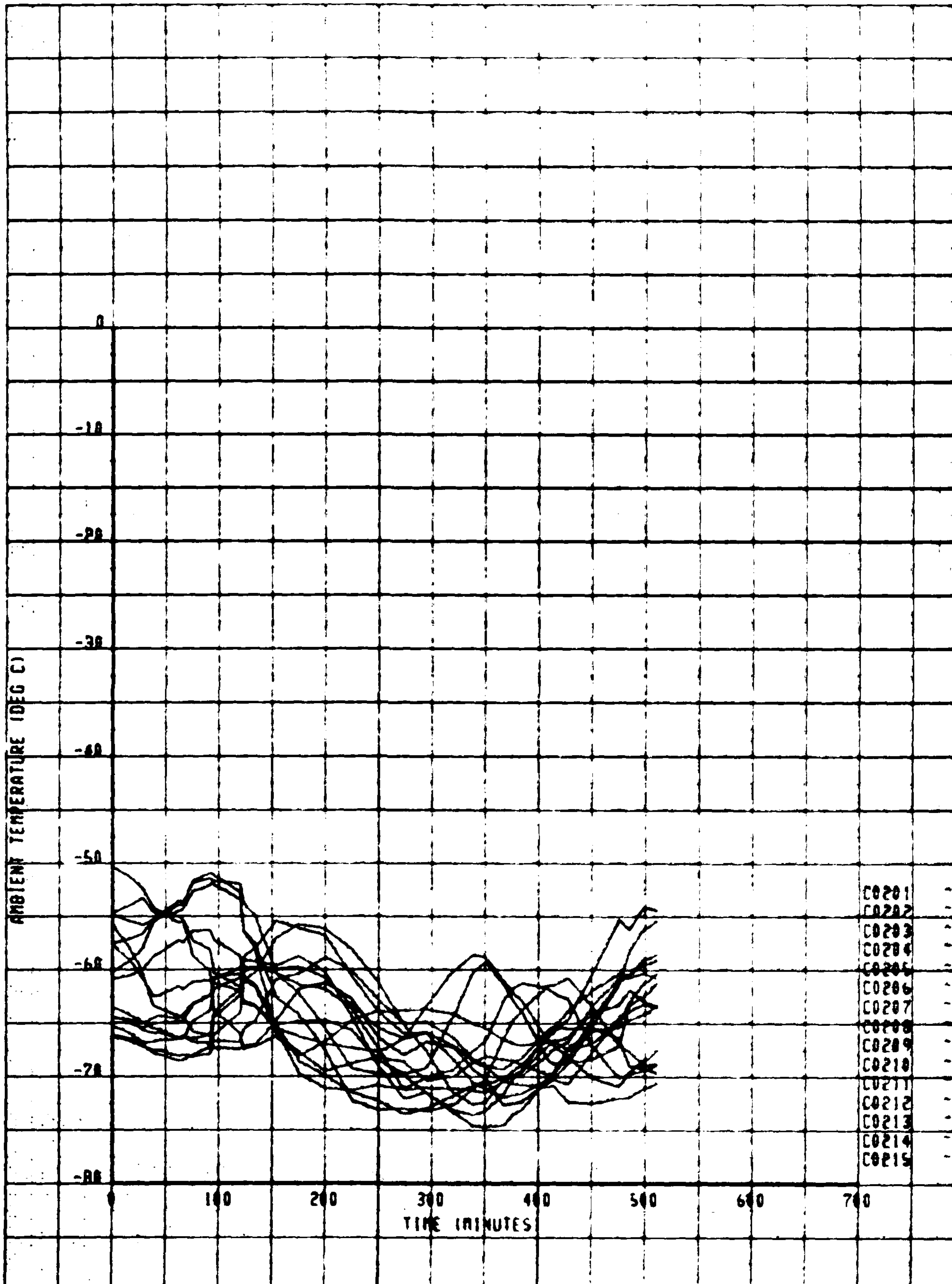

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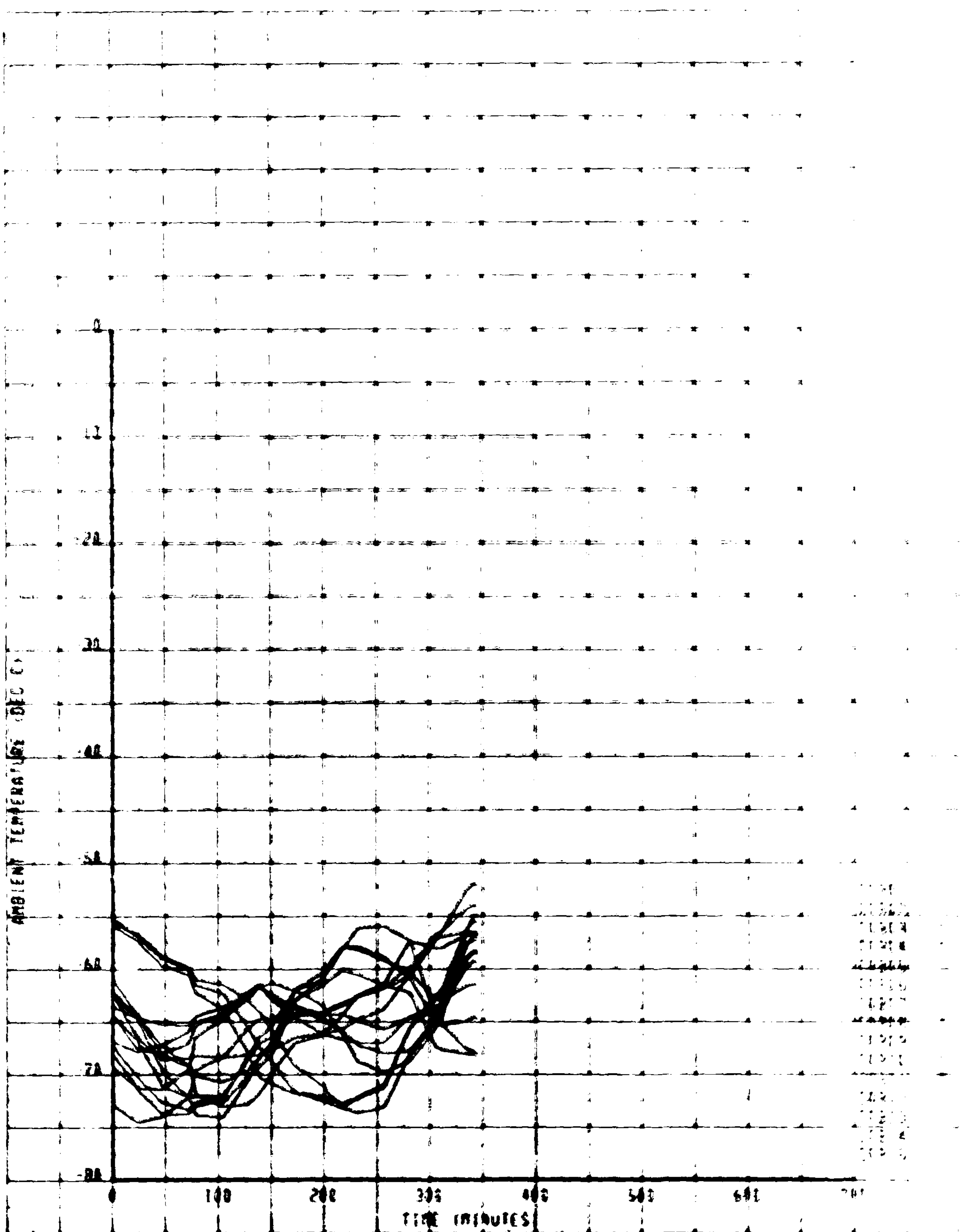
C-141 DATA
TRACK 2
15 WORST CASE COLD DAYS

THE BOEING COMPANY

Figure C-12

PAGE C-13



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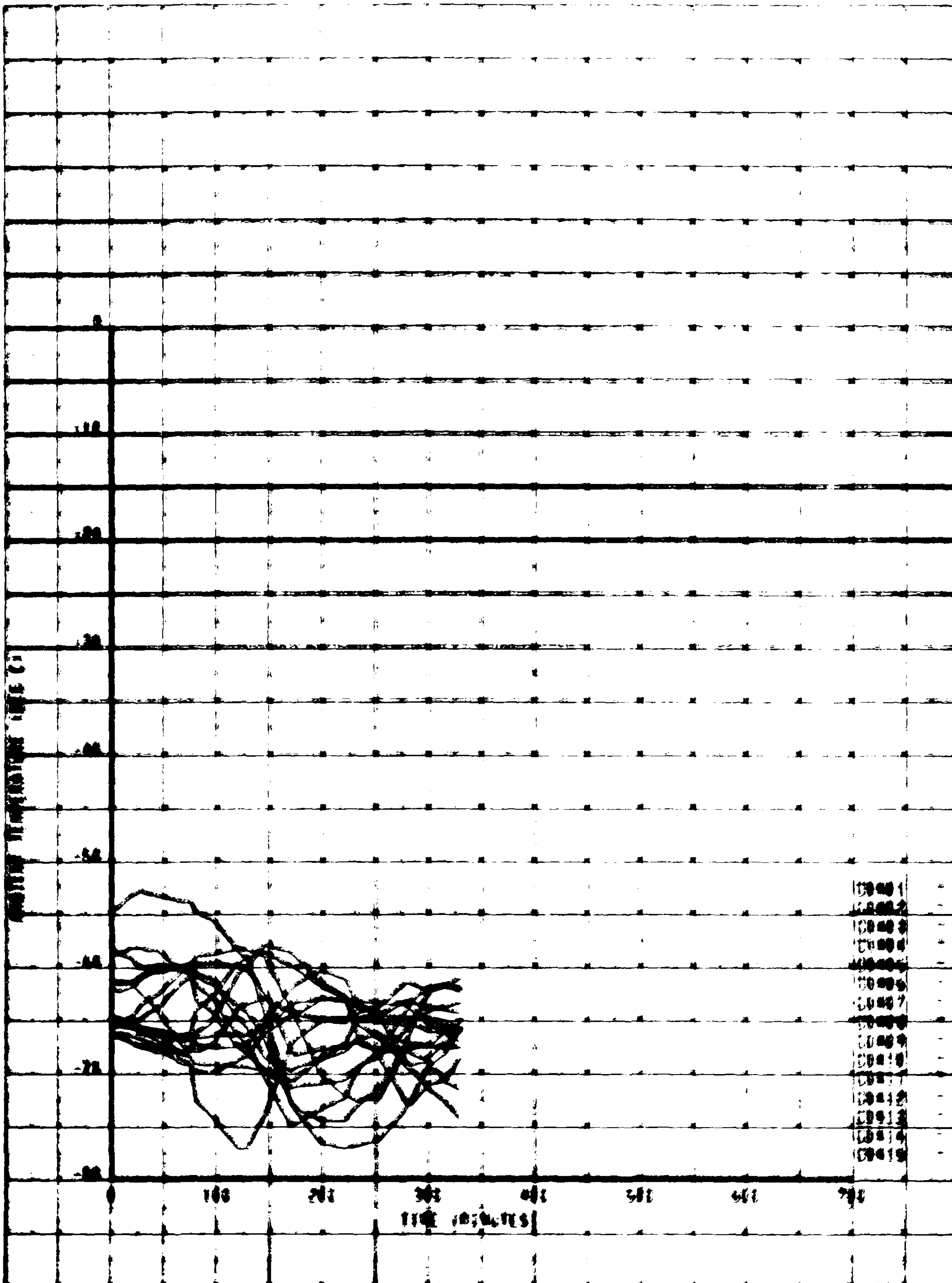

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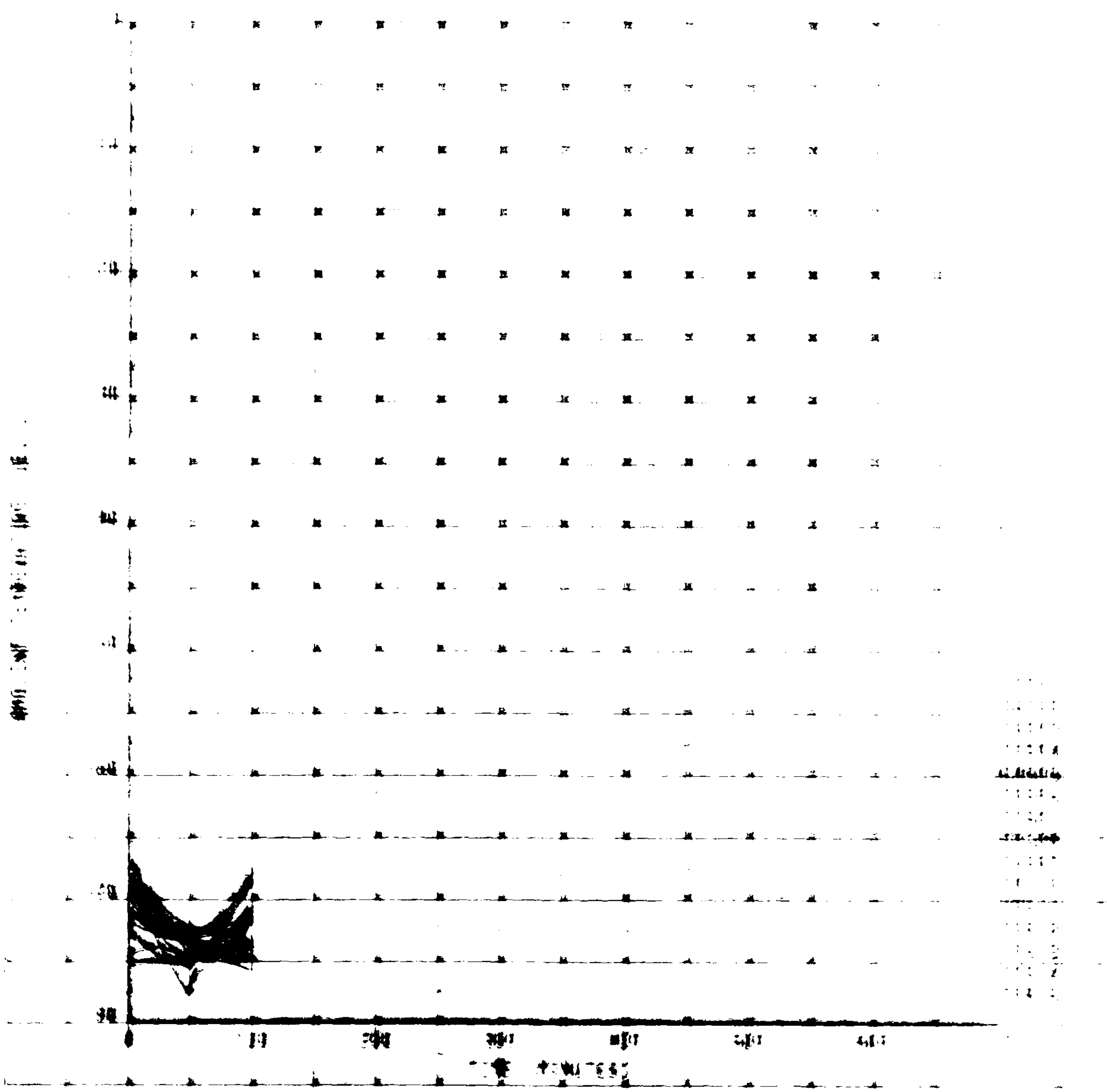
Figure C-14

THE BOEING COMPANY

C-15



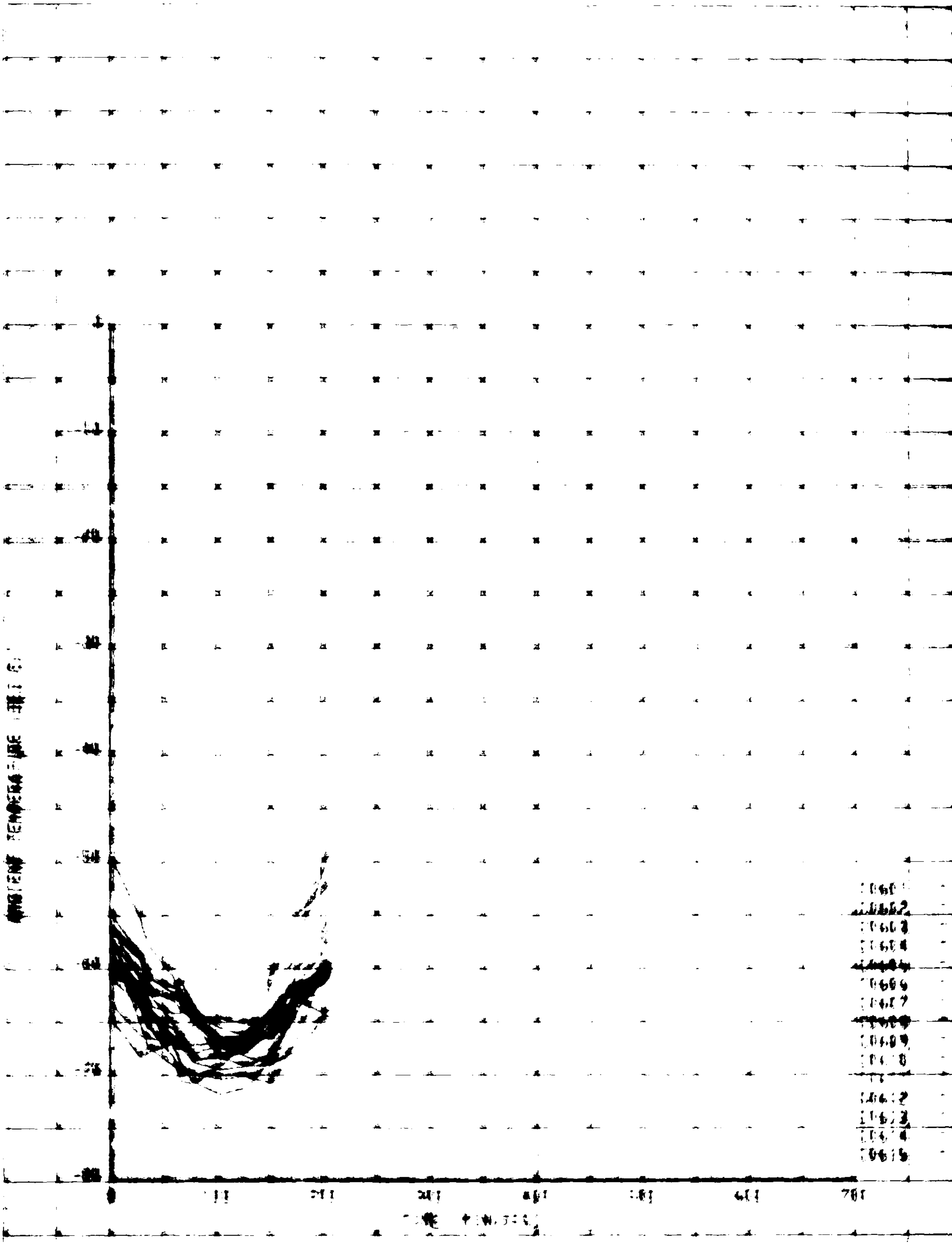
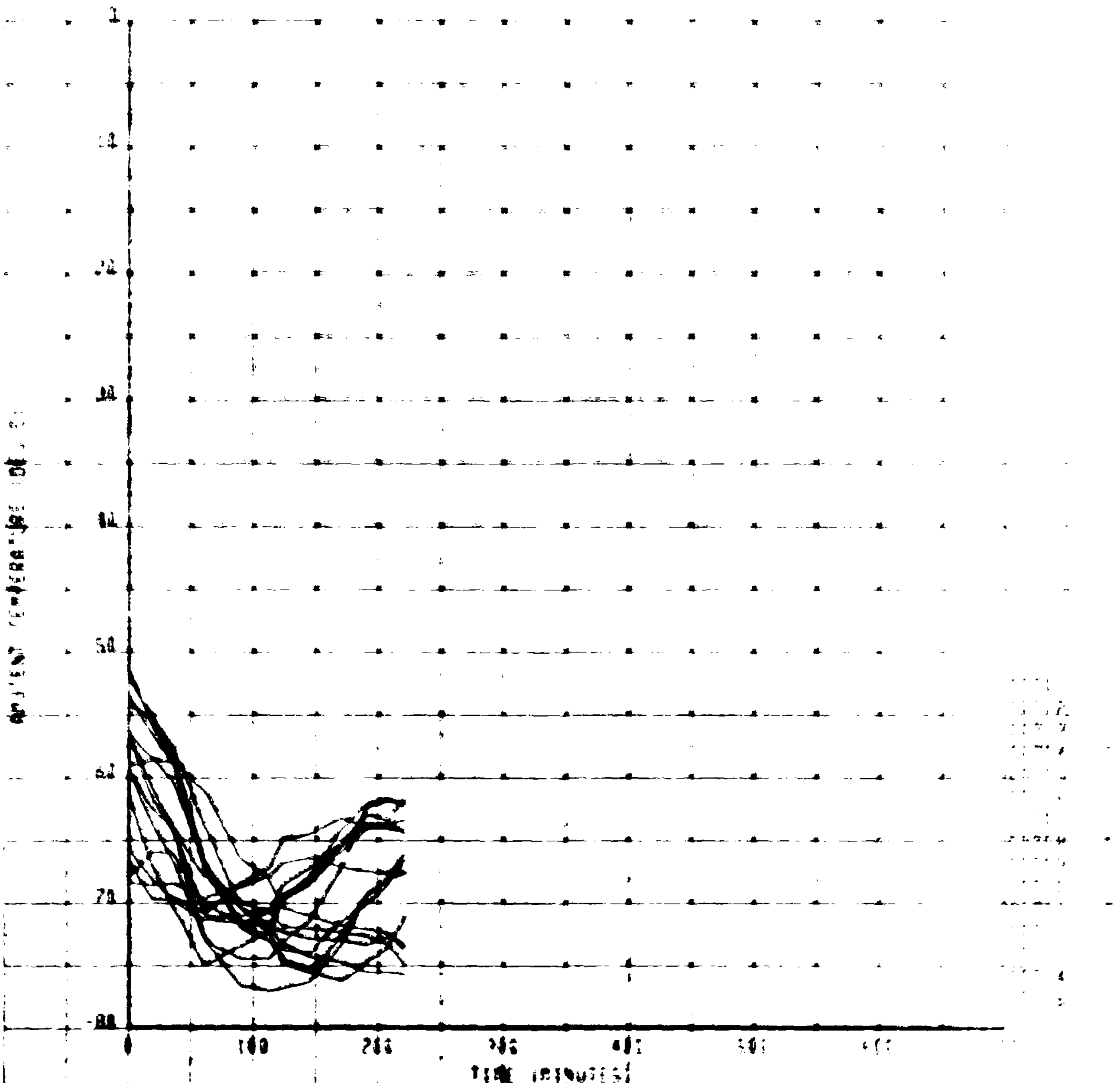


Figure C-16

C-17



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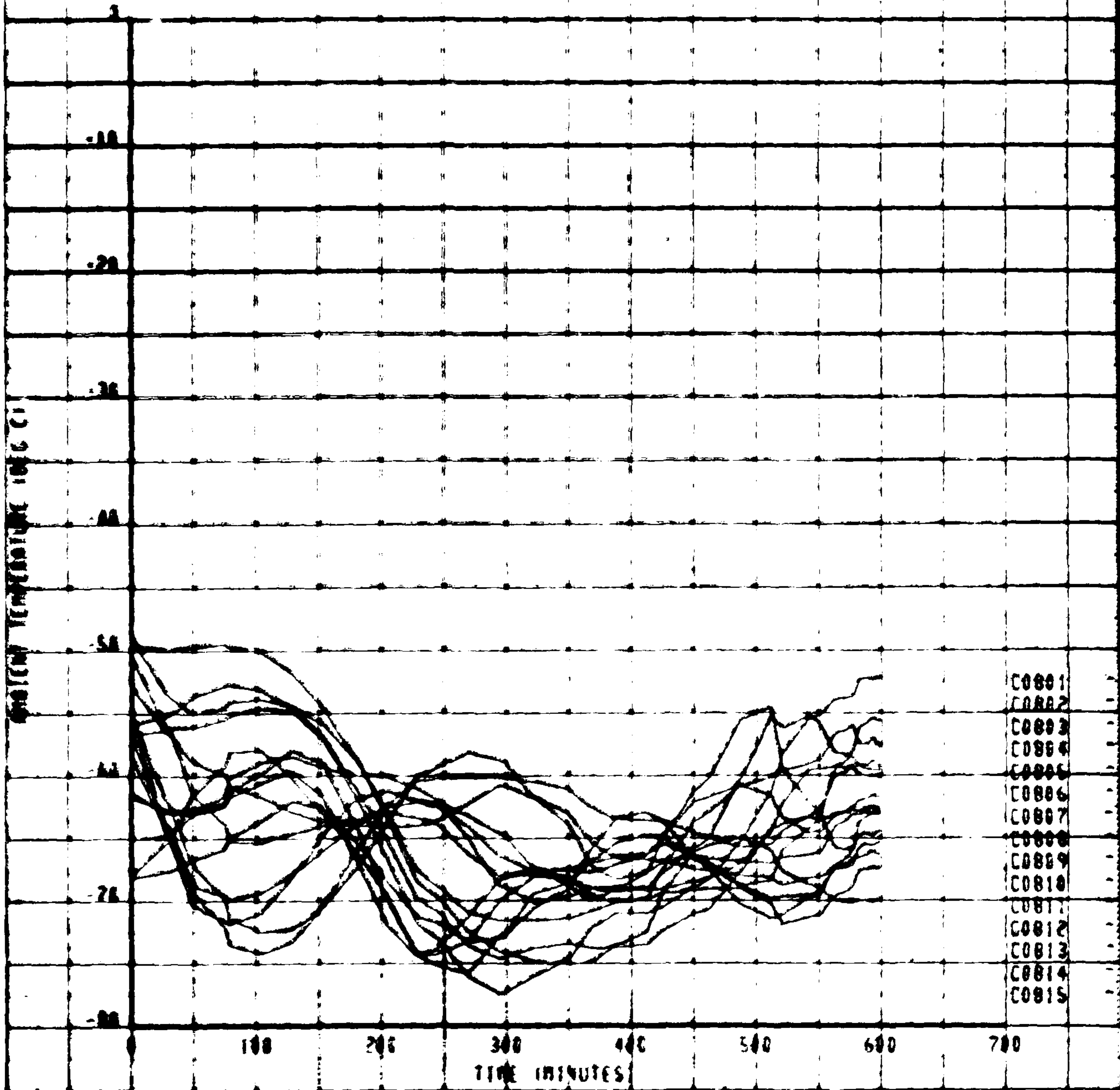
TRACK 7

15 WORST CASE COLD DAYS

THE BOEING COMPANY

Figure C-17

C-18



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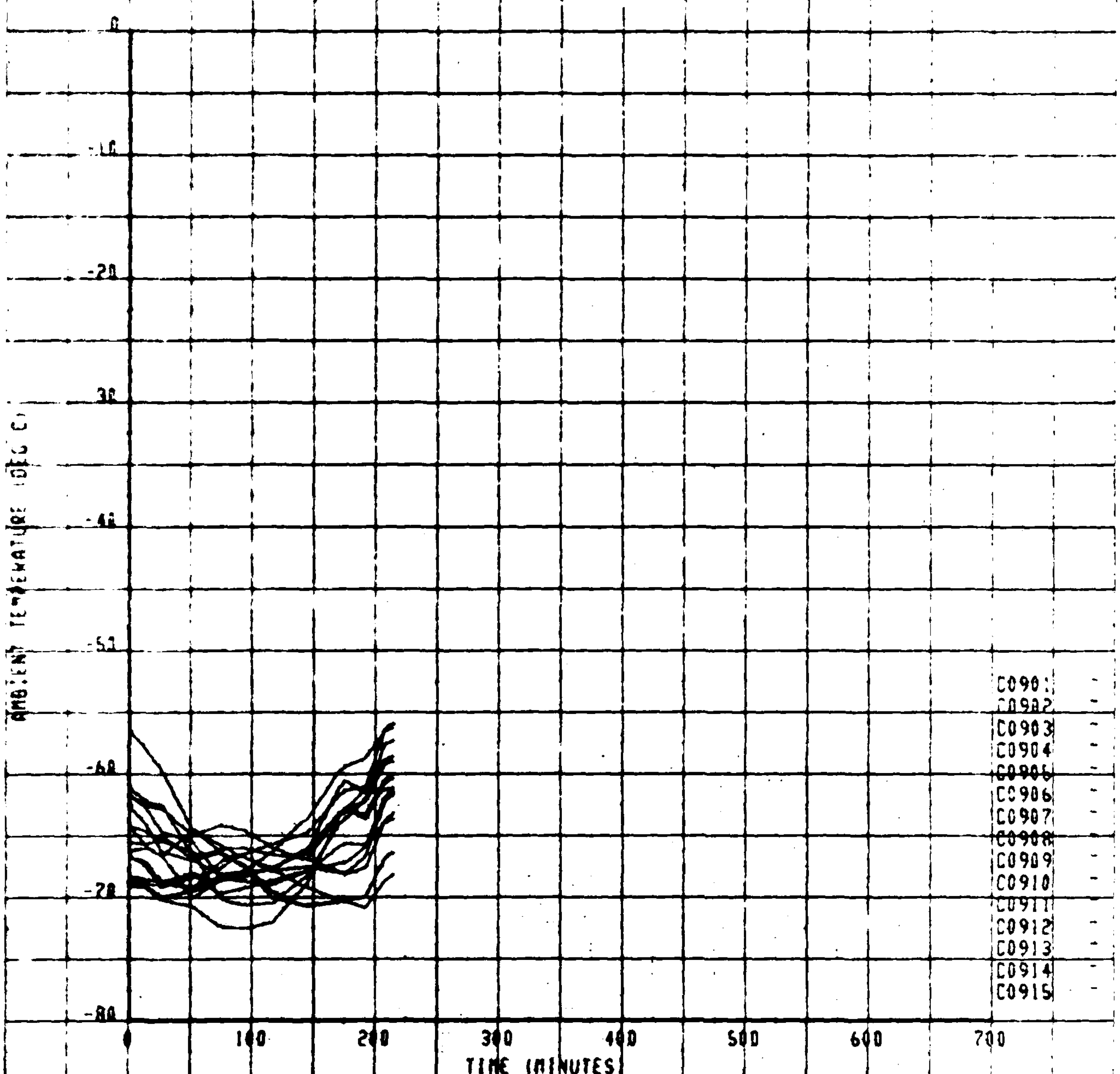

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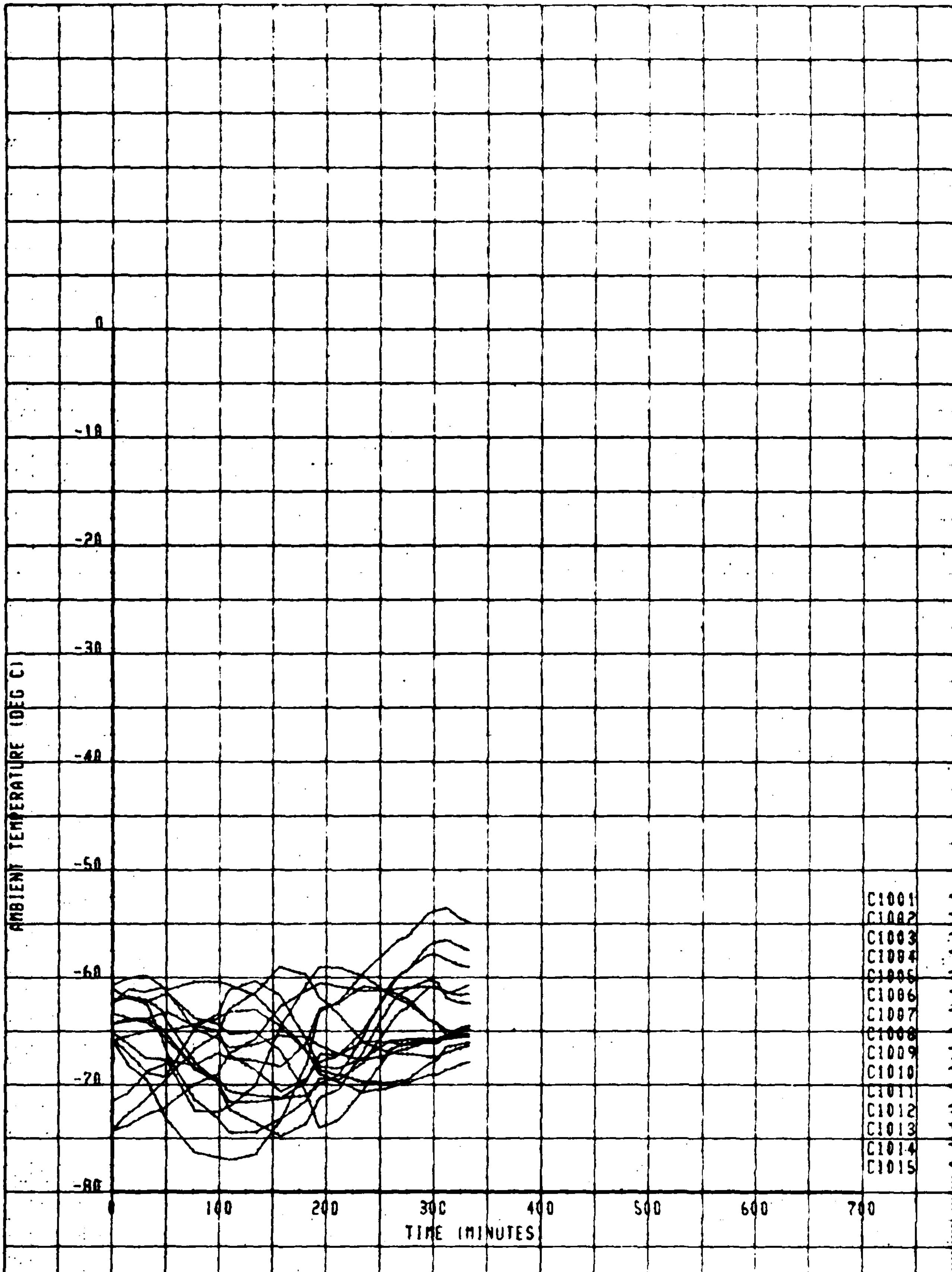
C-141 DATA
TRACK 9
15 WORST CASE COLD DAYS

Figure C-19

THE BOEING COMPANY

PAGE C-20



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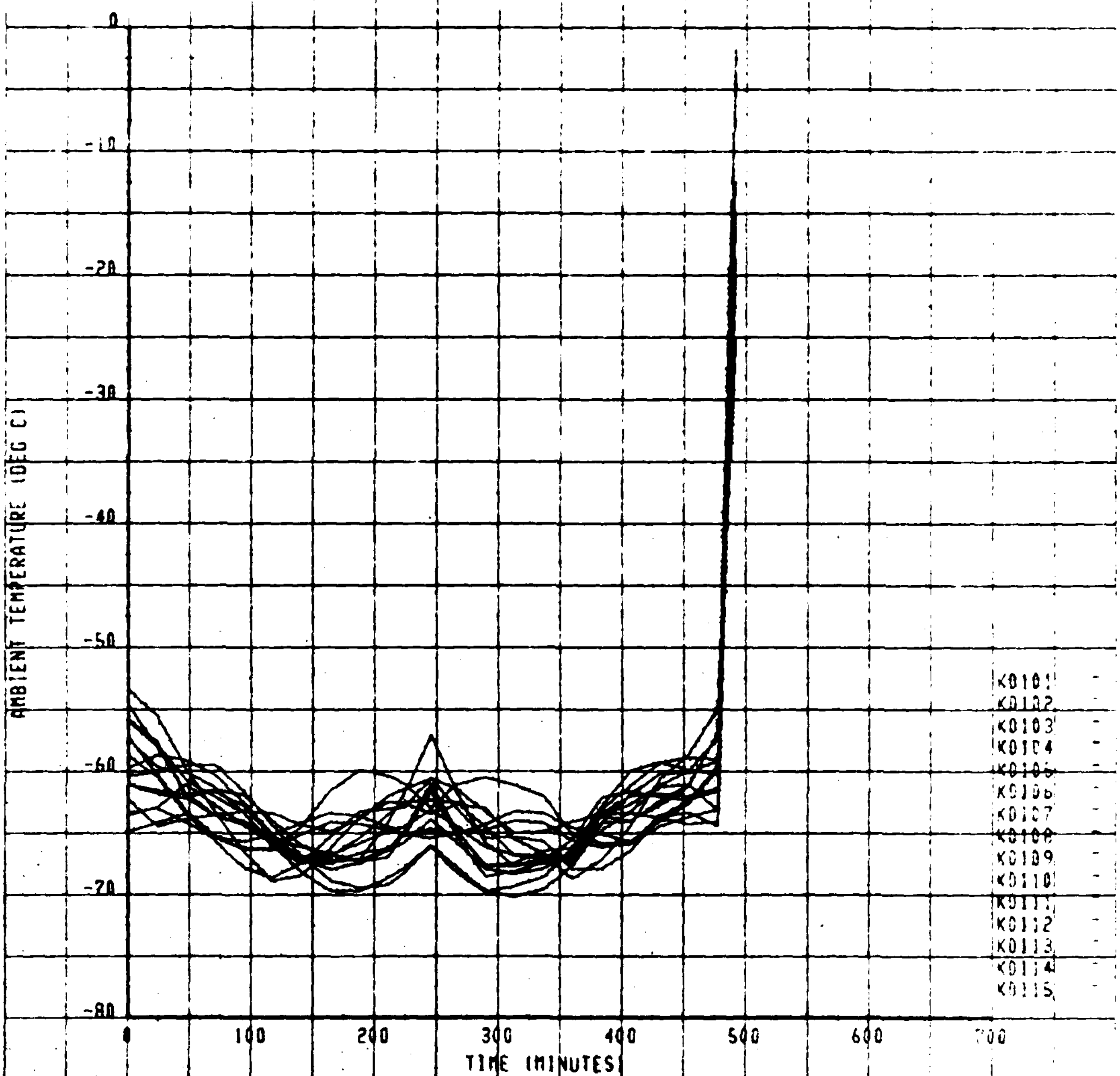

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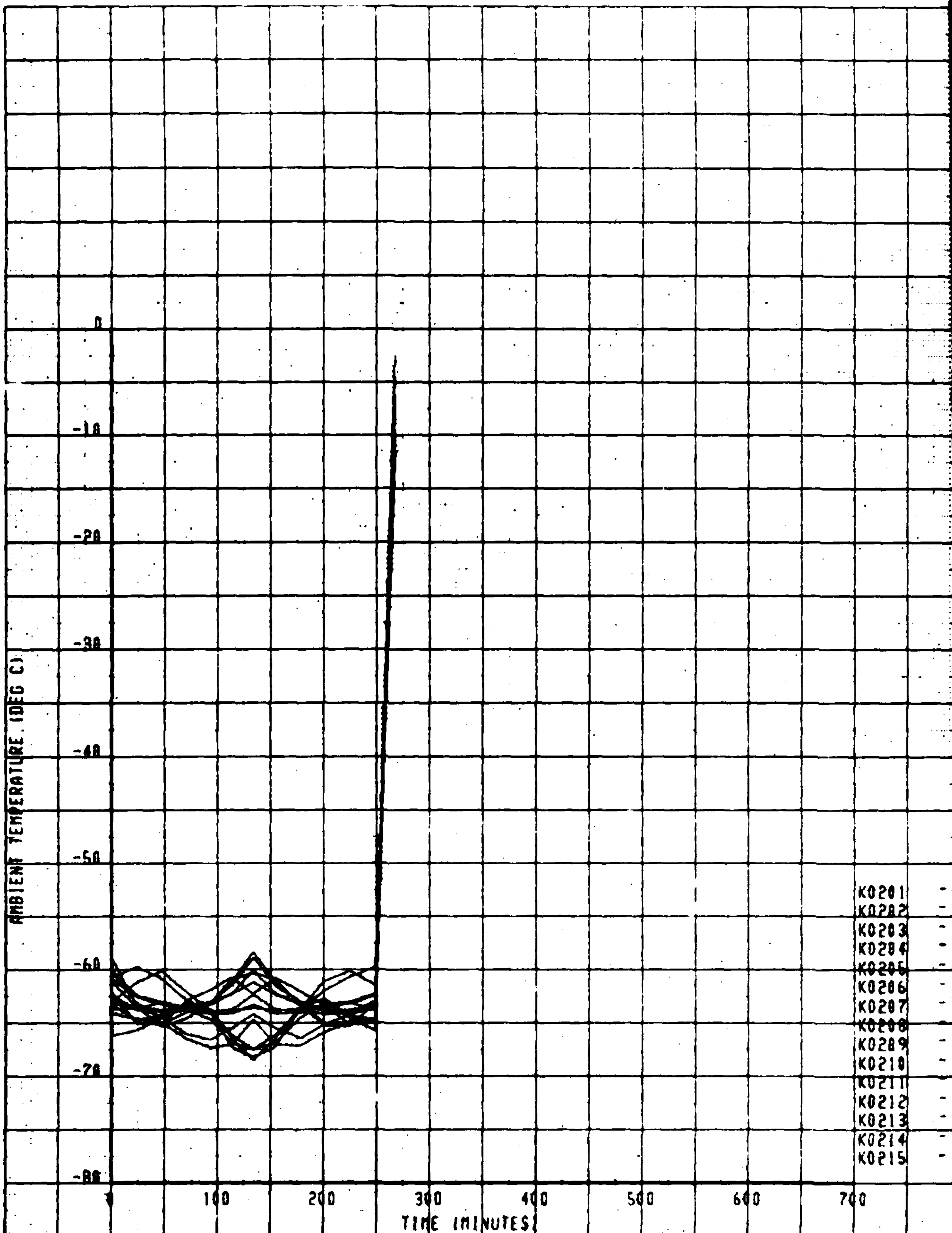

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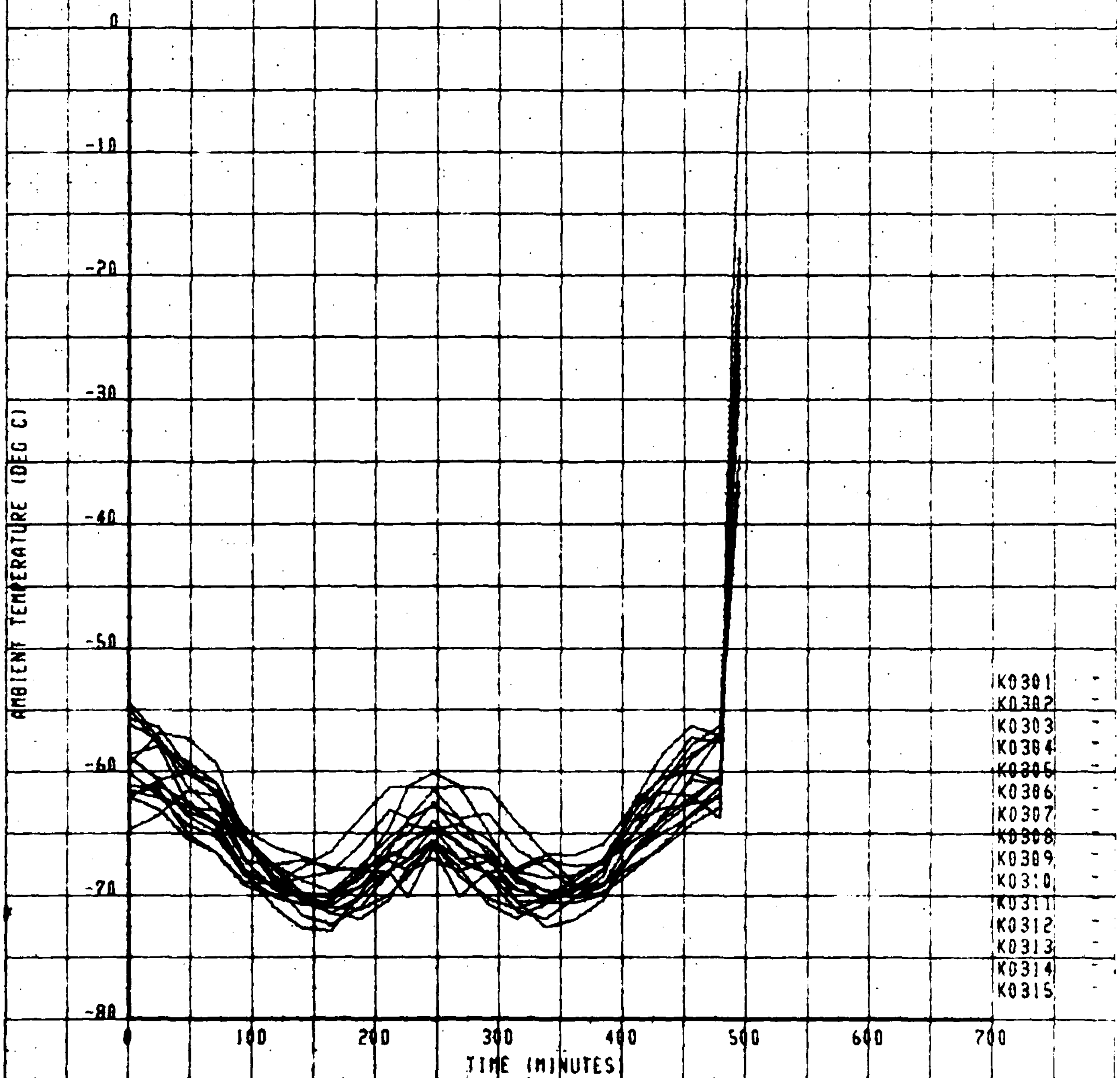

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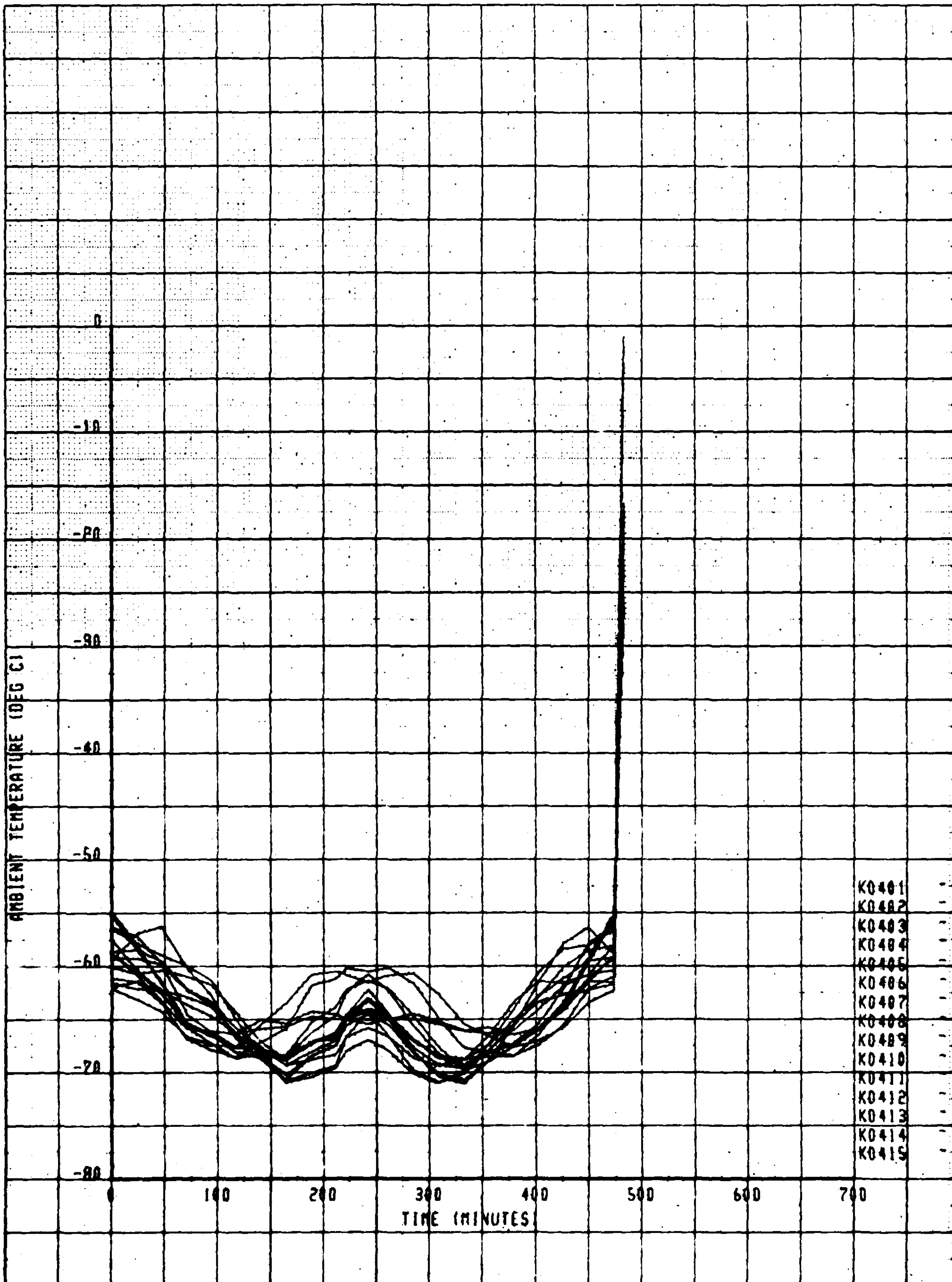

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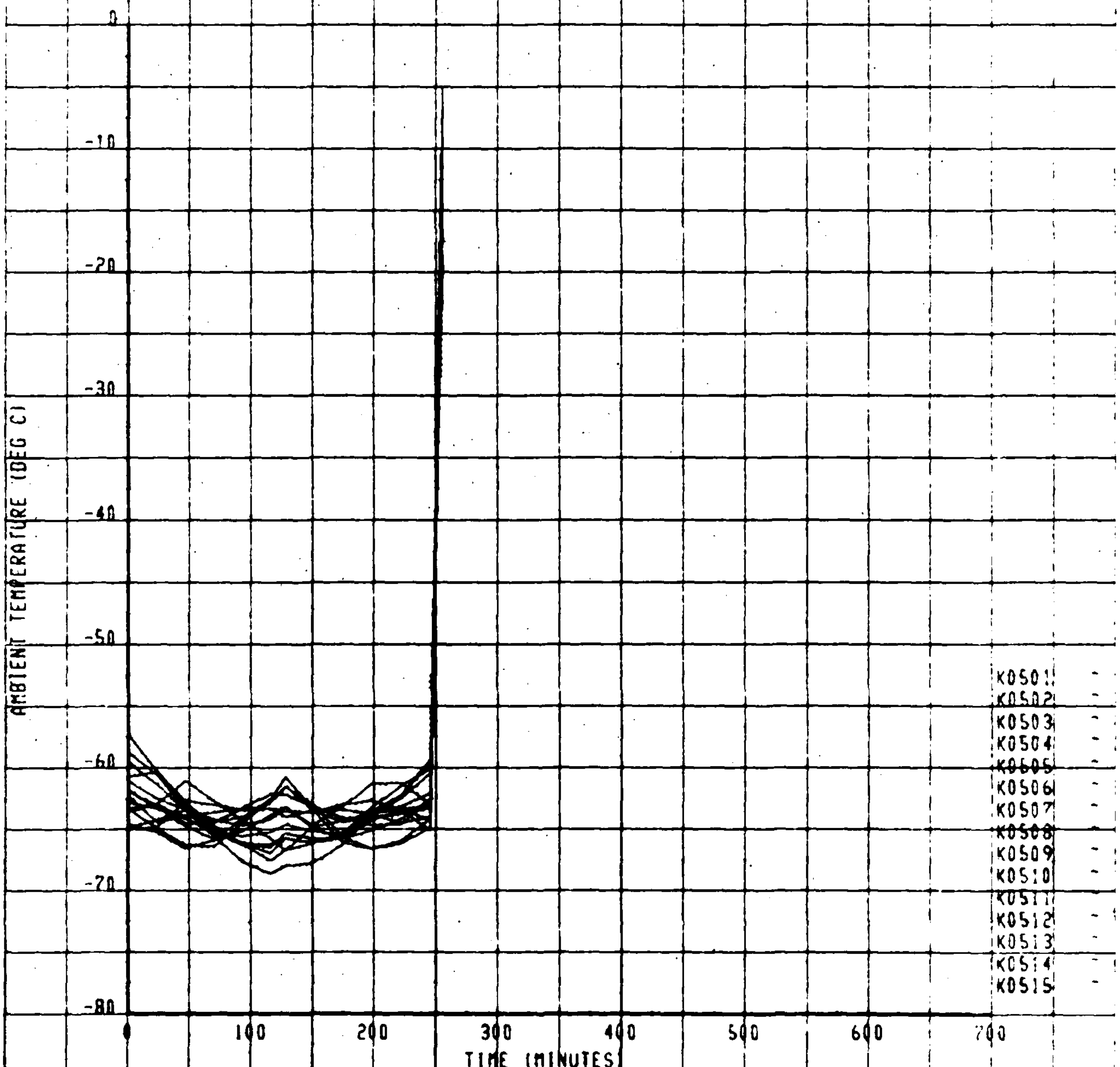

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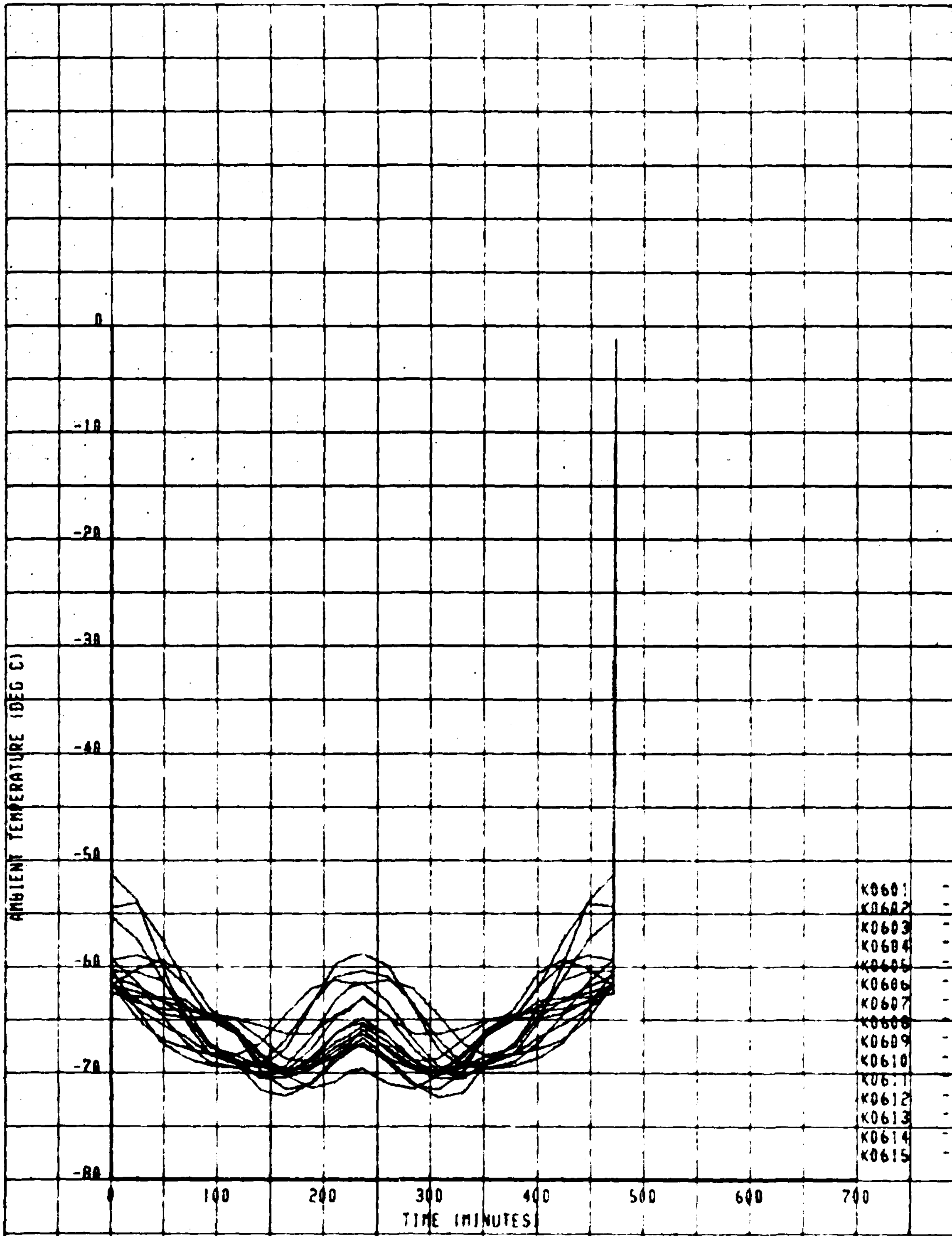
Figure C-25

PAGE C-26



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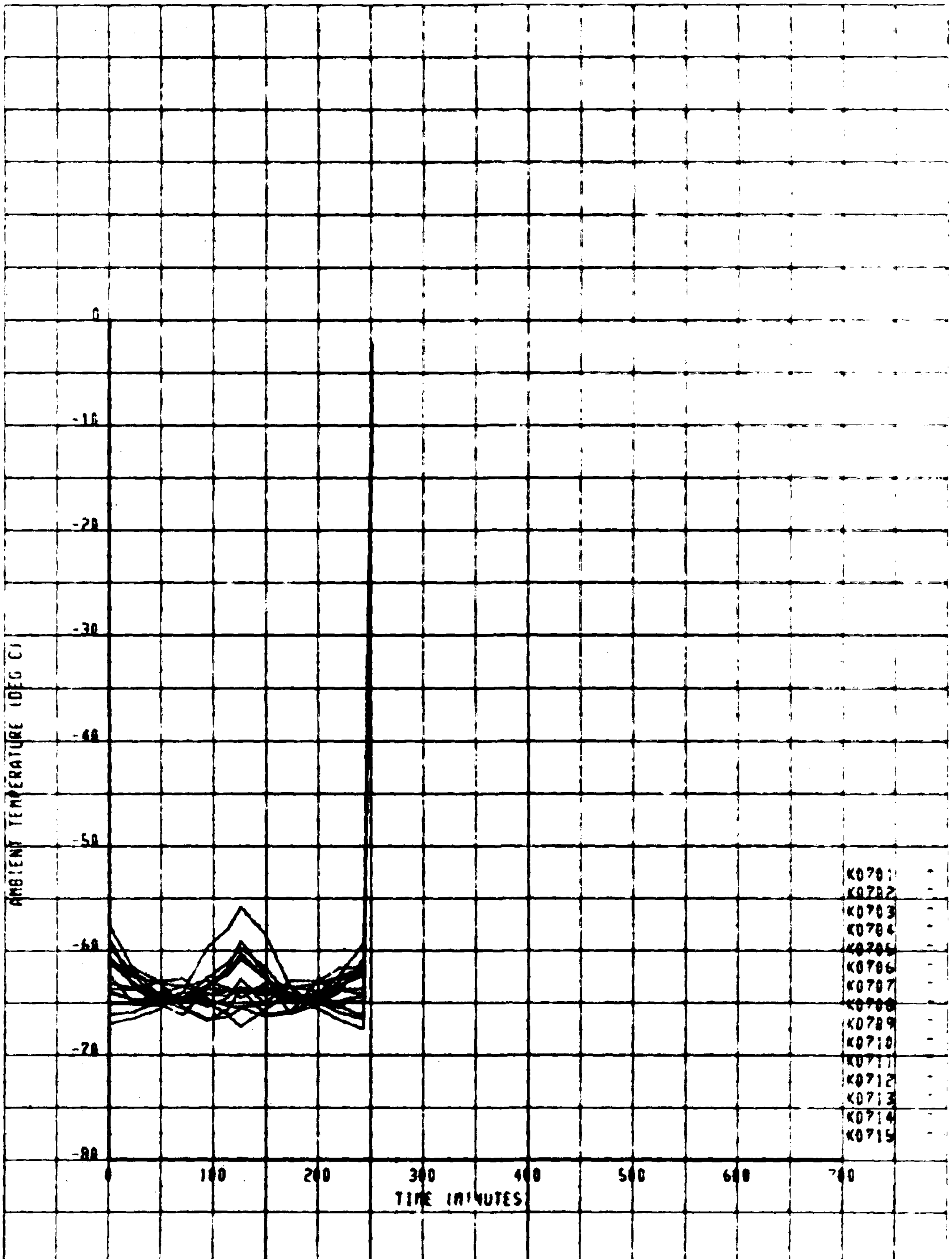

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KC-135 DATA
TRACK 7
15 WORST CASE COLD DAYS

THE BOEING COMPANY

Figure C-27

PAGE C-28

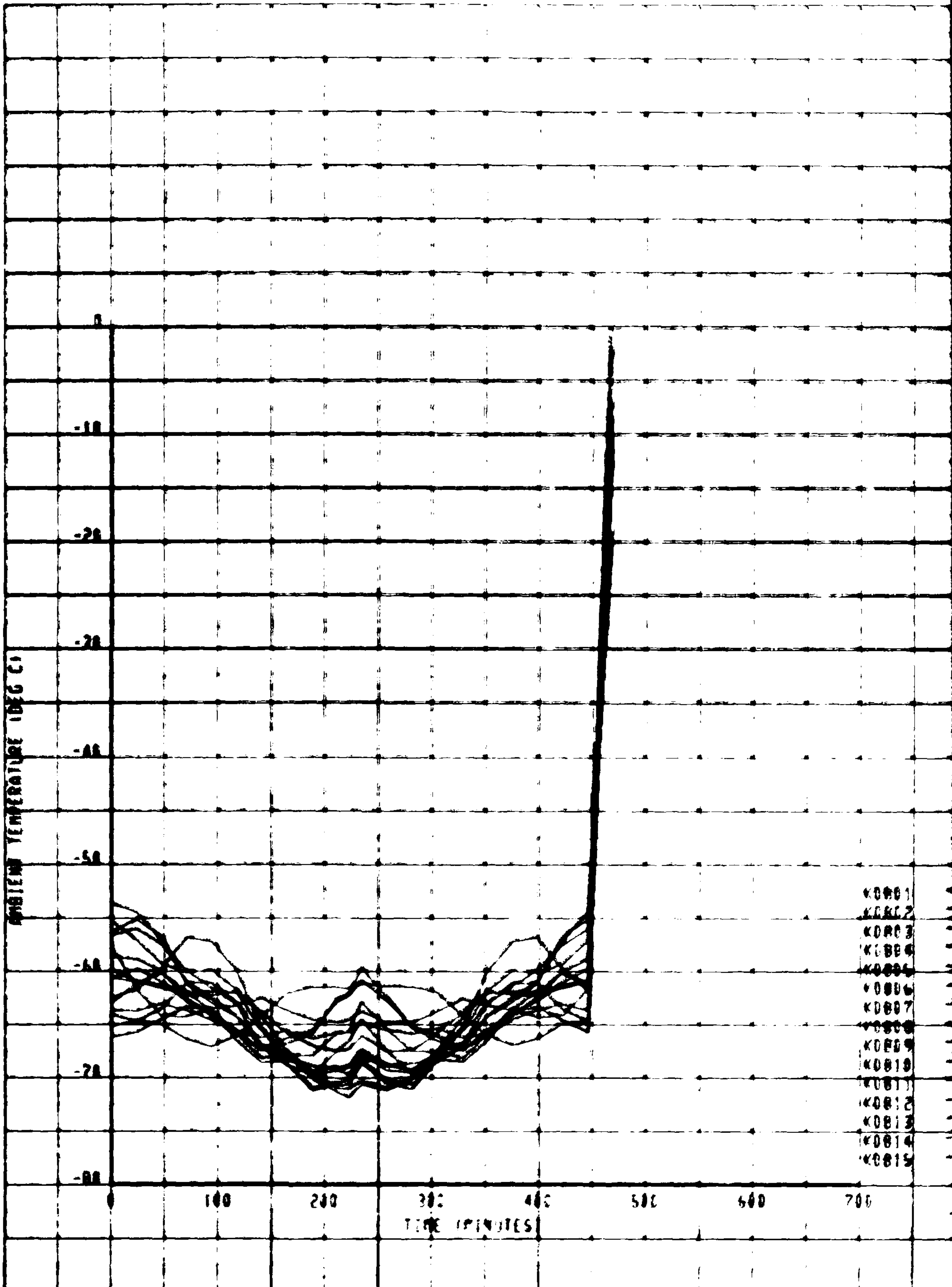

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Figure C-29

PAGE C-29

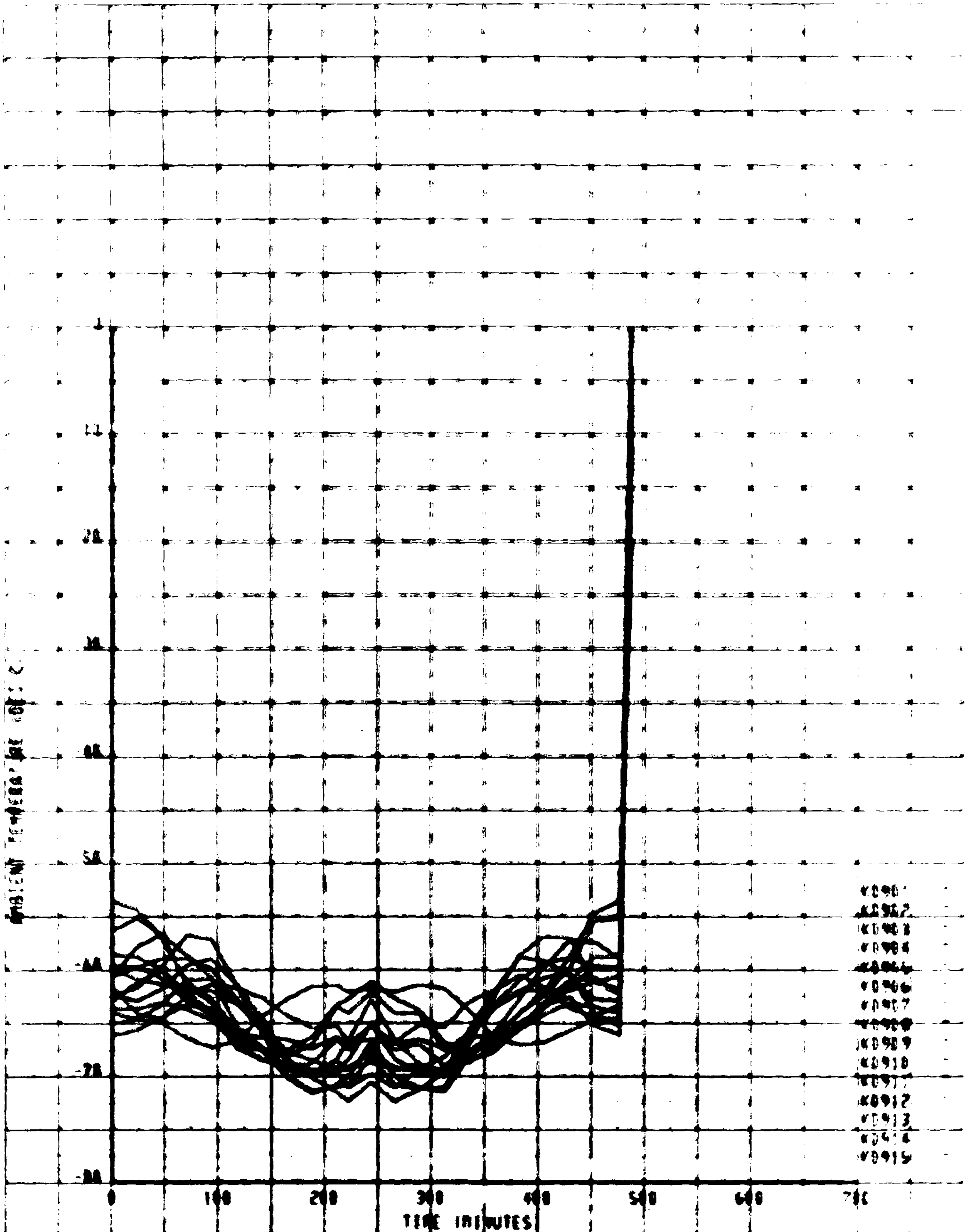

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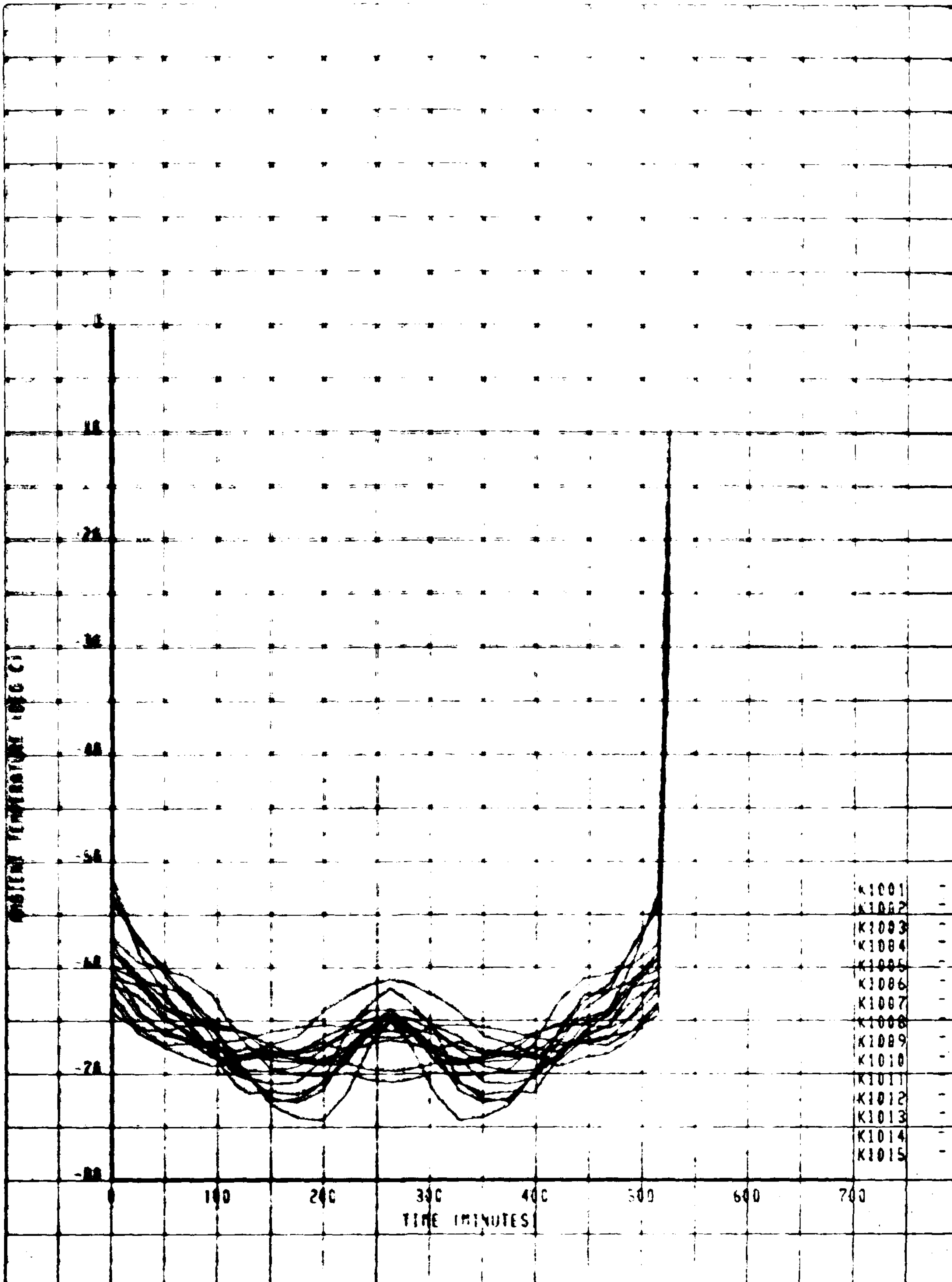
Figure C-29

PAGE C-30



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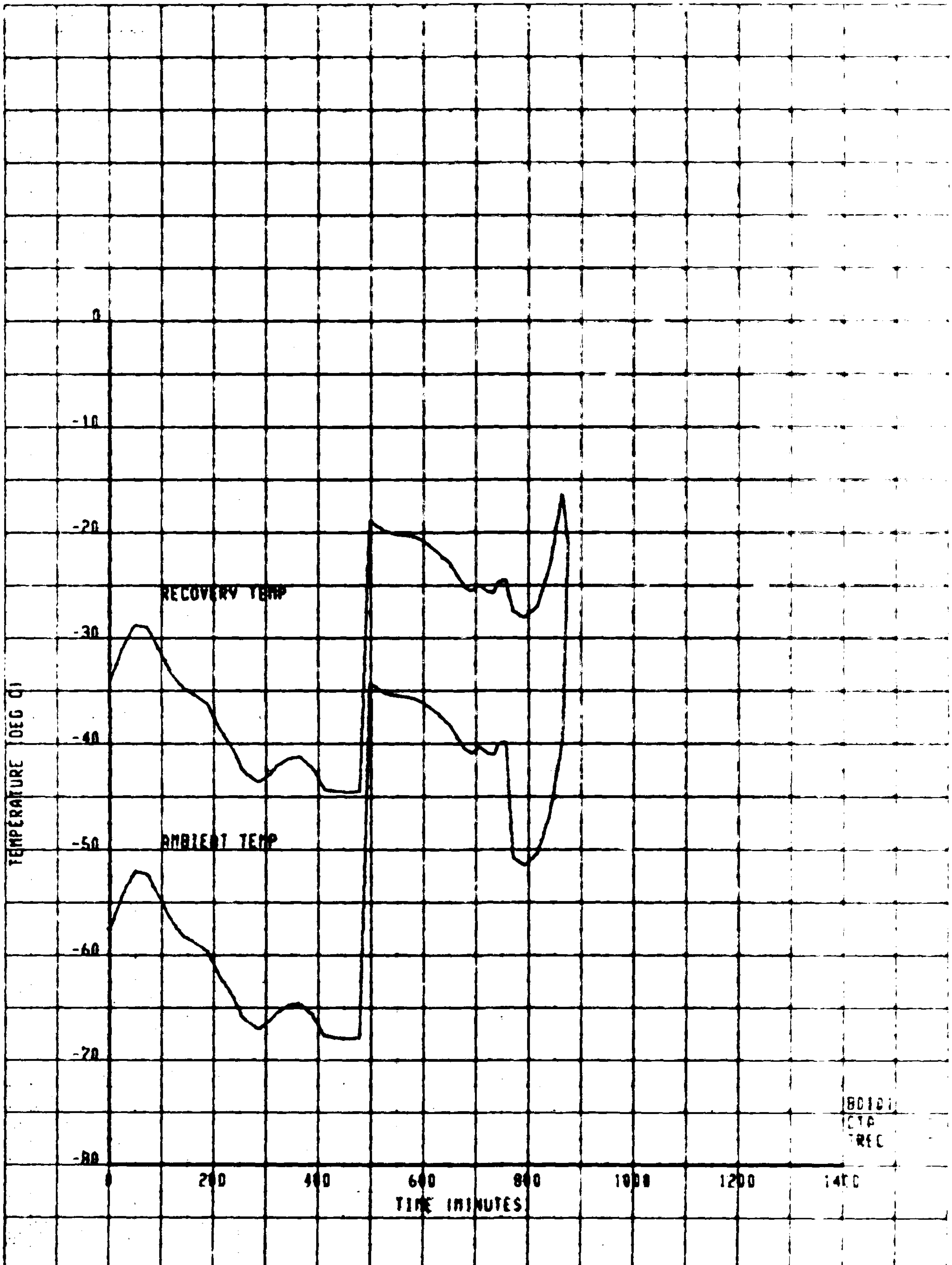
KC-135 DATA
TRACK
15 WORST CASE COLD DAYS

THE BOEING COMPANY

Figure C-30

PAGE C-31



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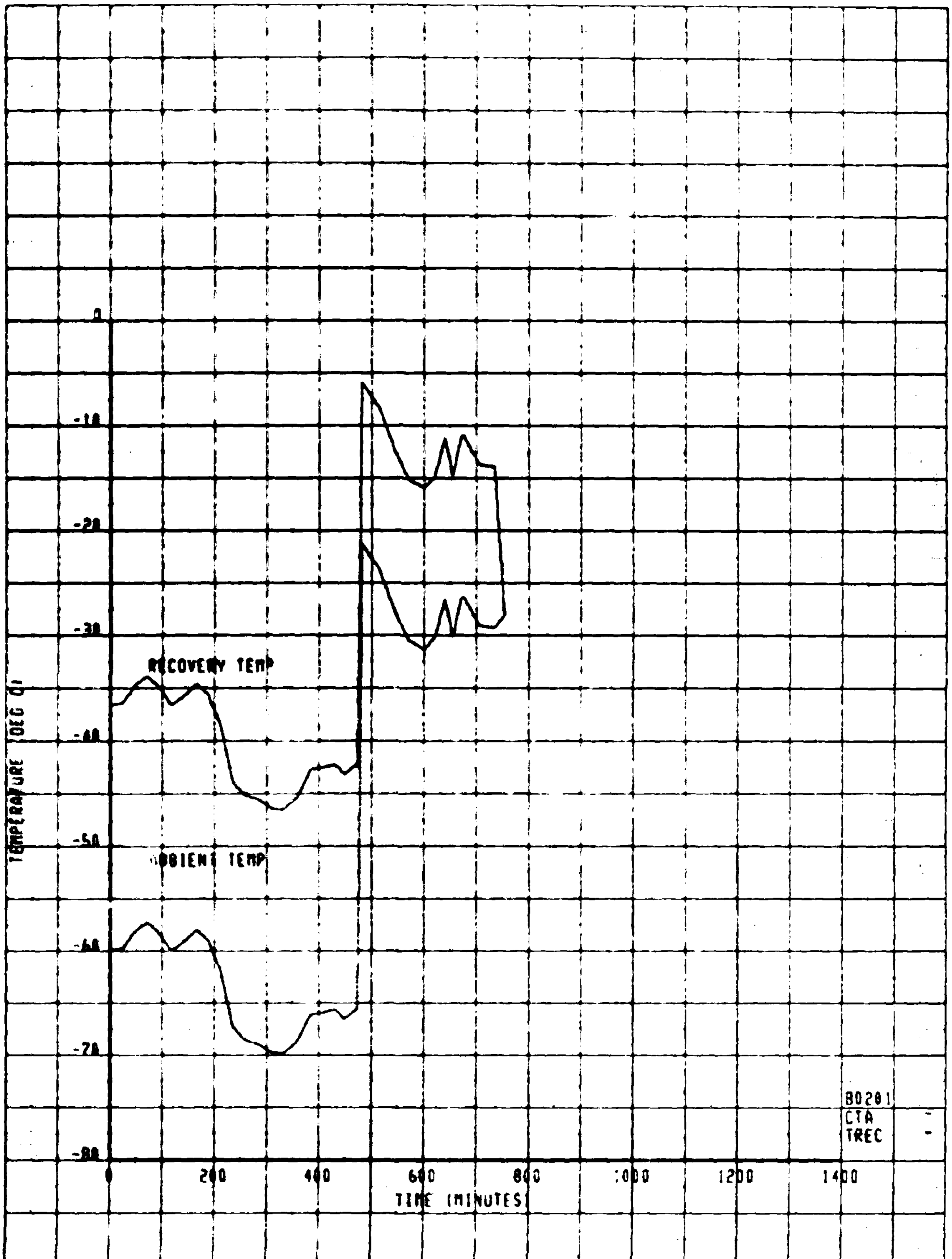

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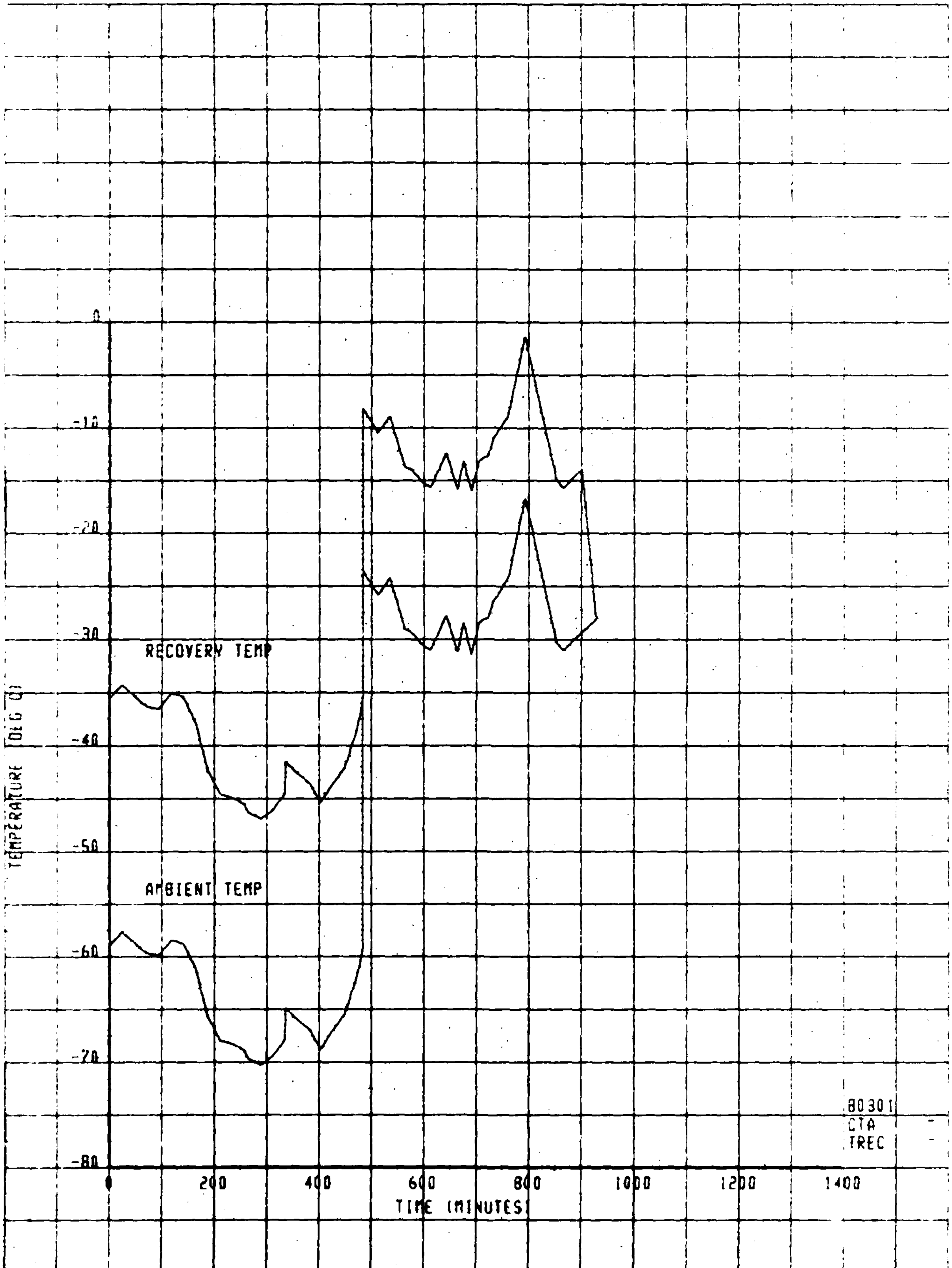
B-52 DATA
TRACK 2
WORST CASE COLD DAY

THE BOEING COMPANY

Figure C-32

PAGE C-33



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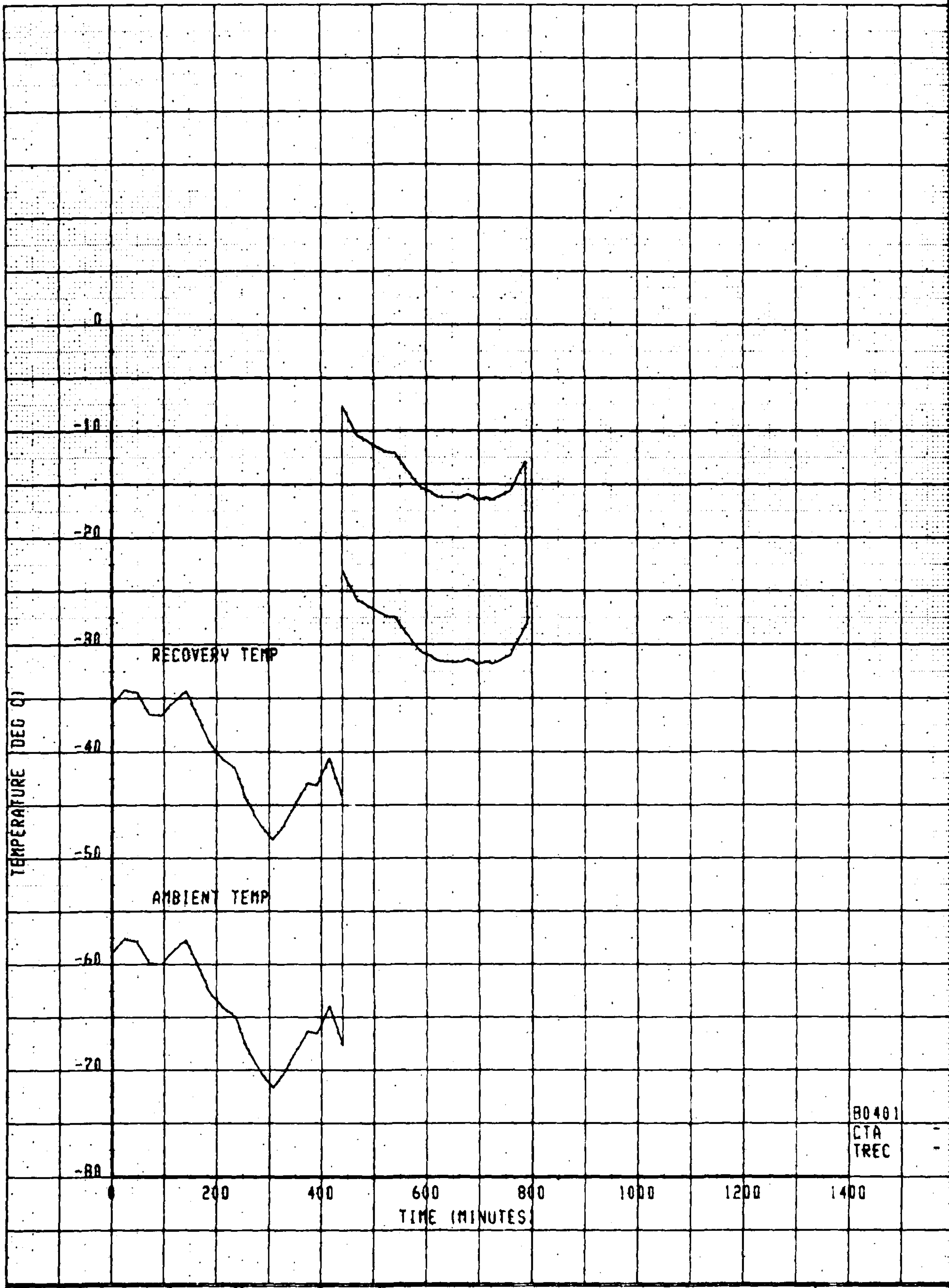

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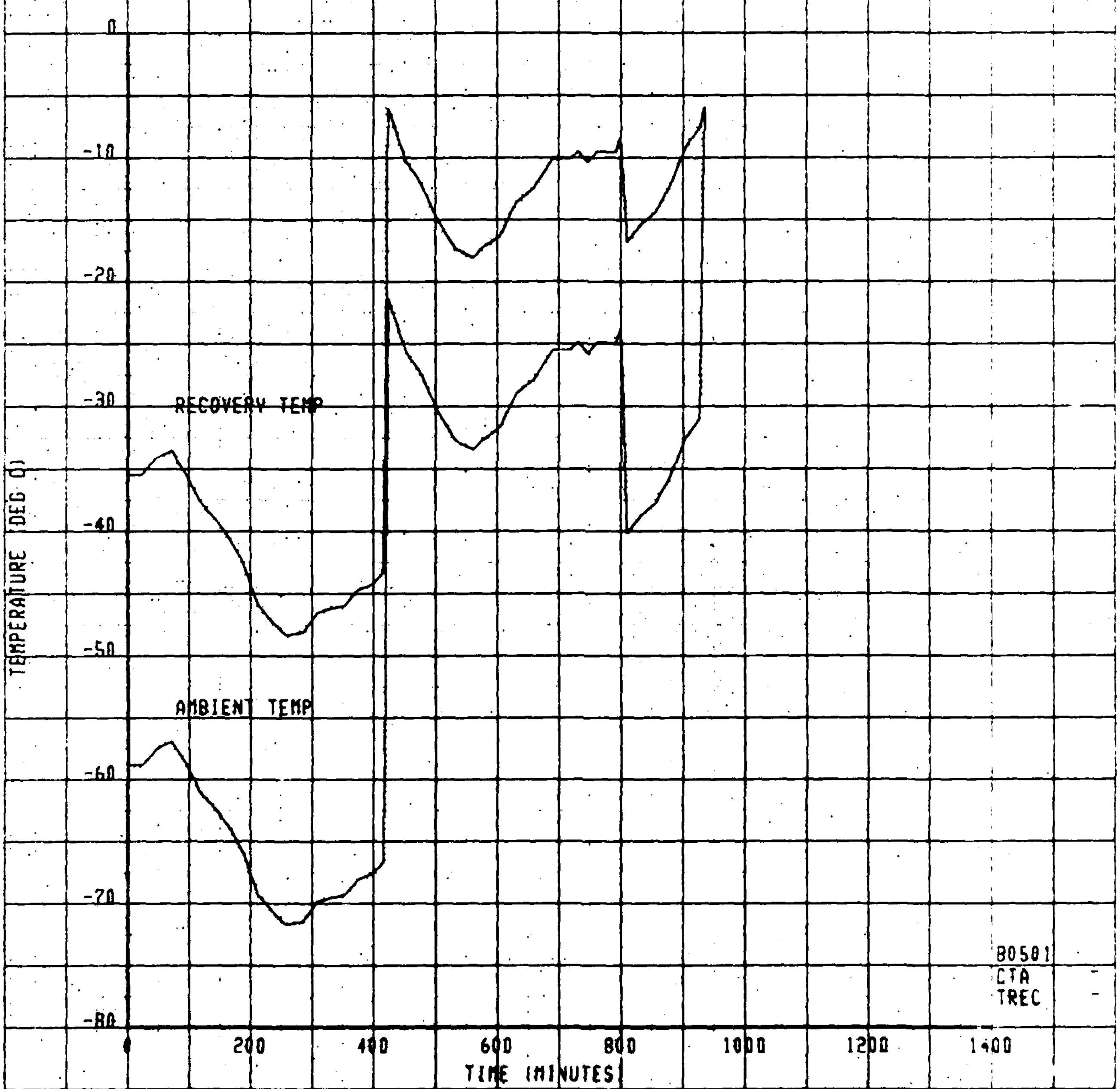

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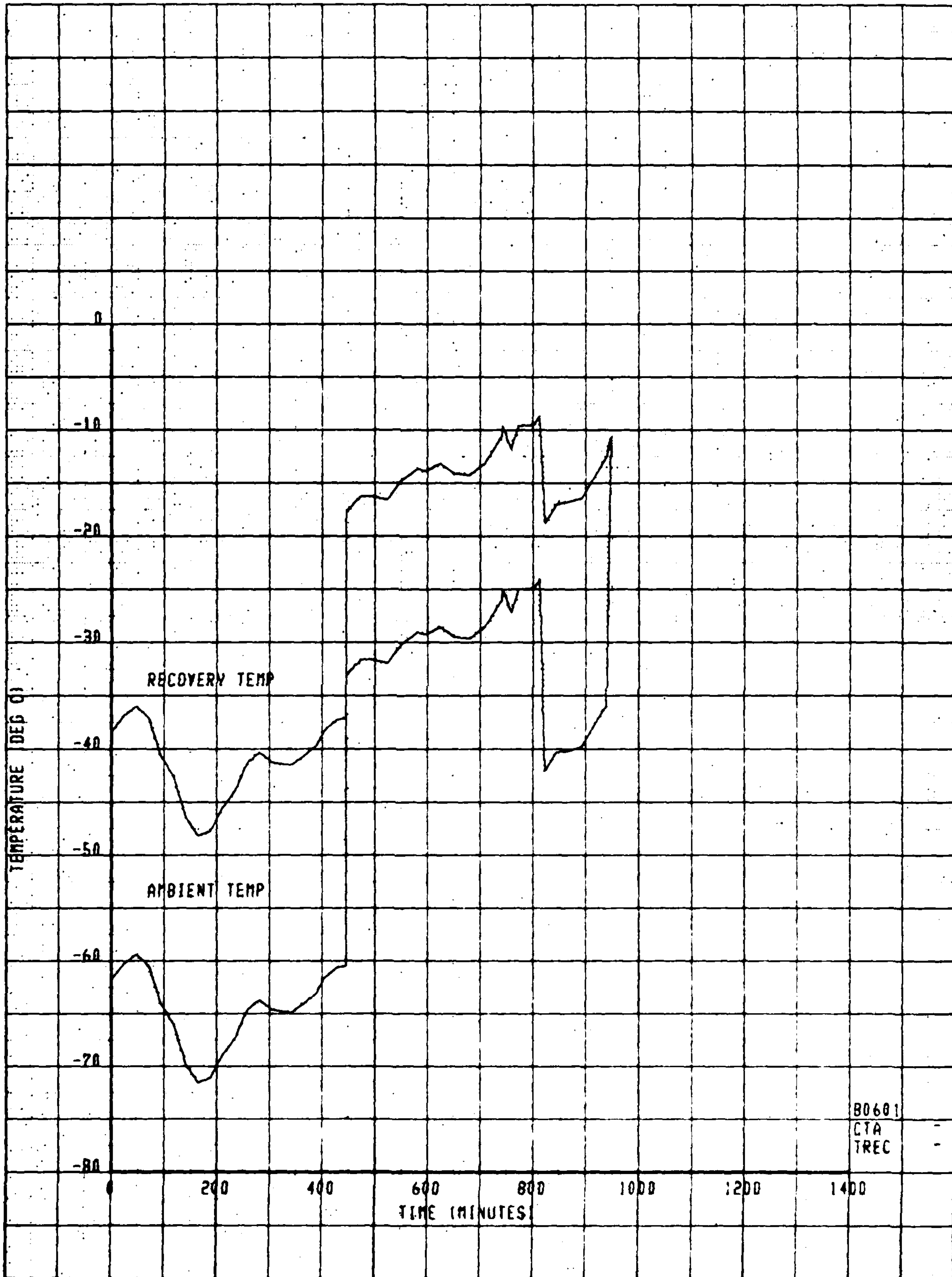

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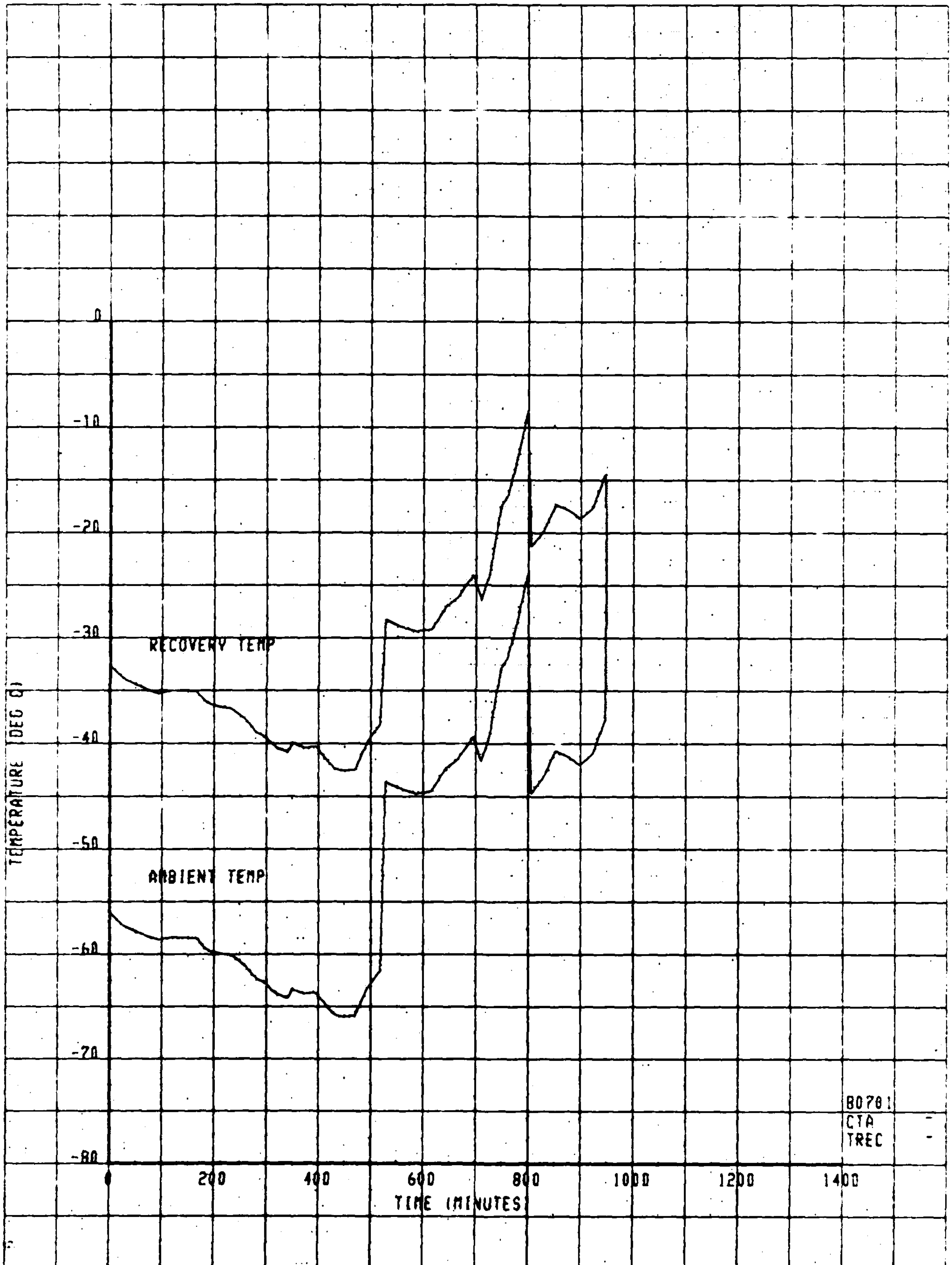

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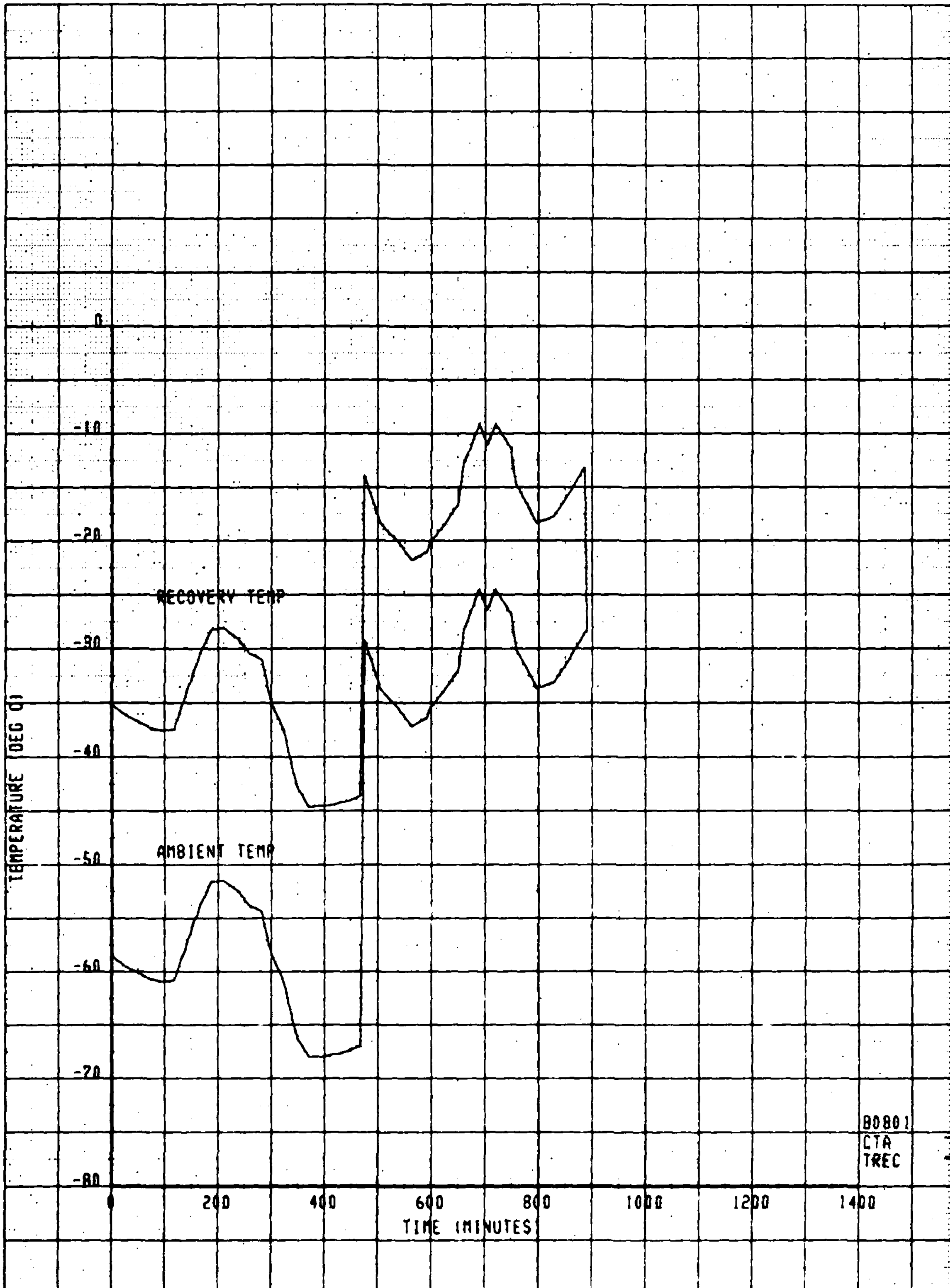

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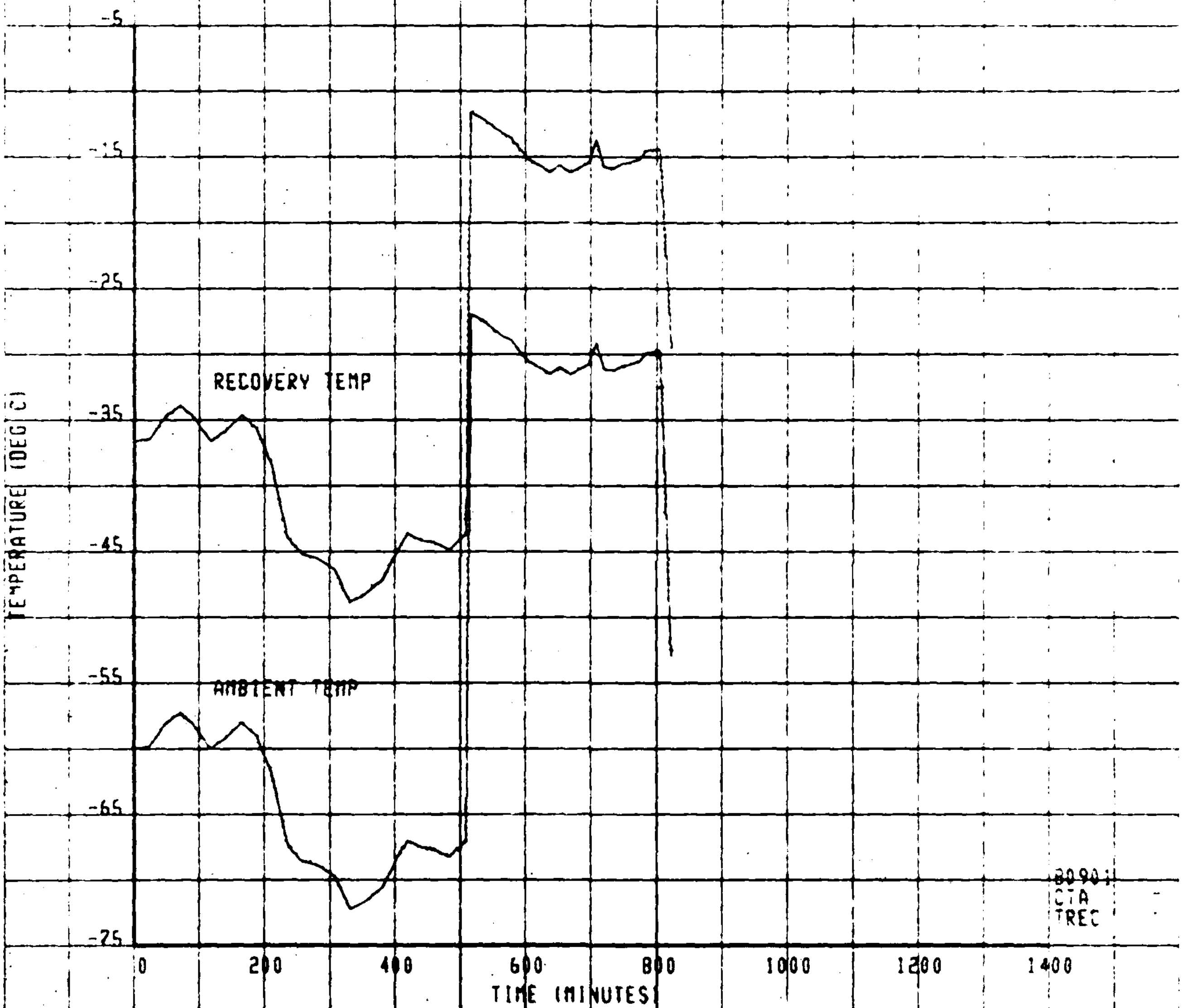

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APPD.					THE BOEING COMPANY

Figure C-39

PAGE C-40

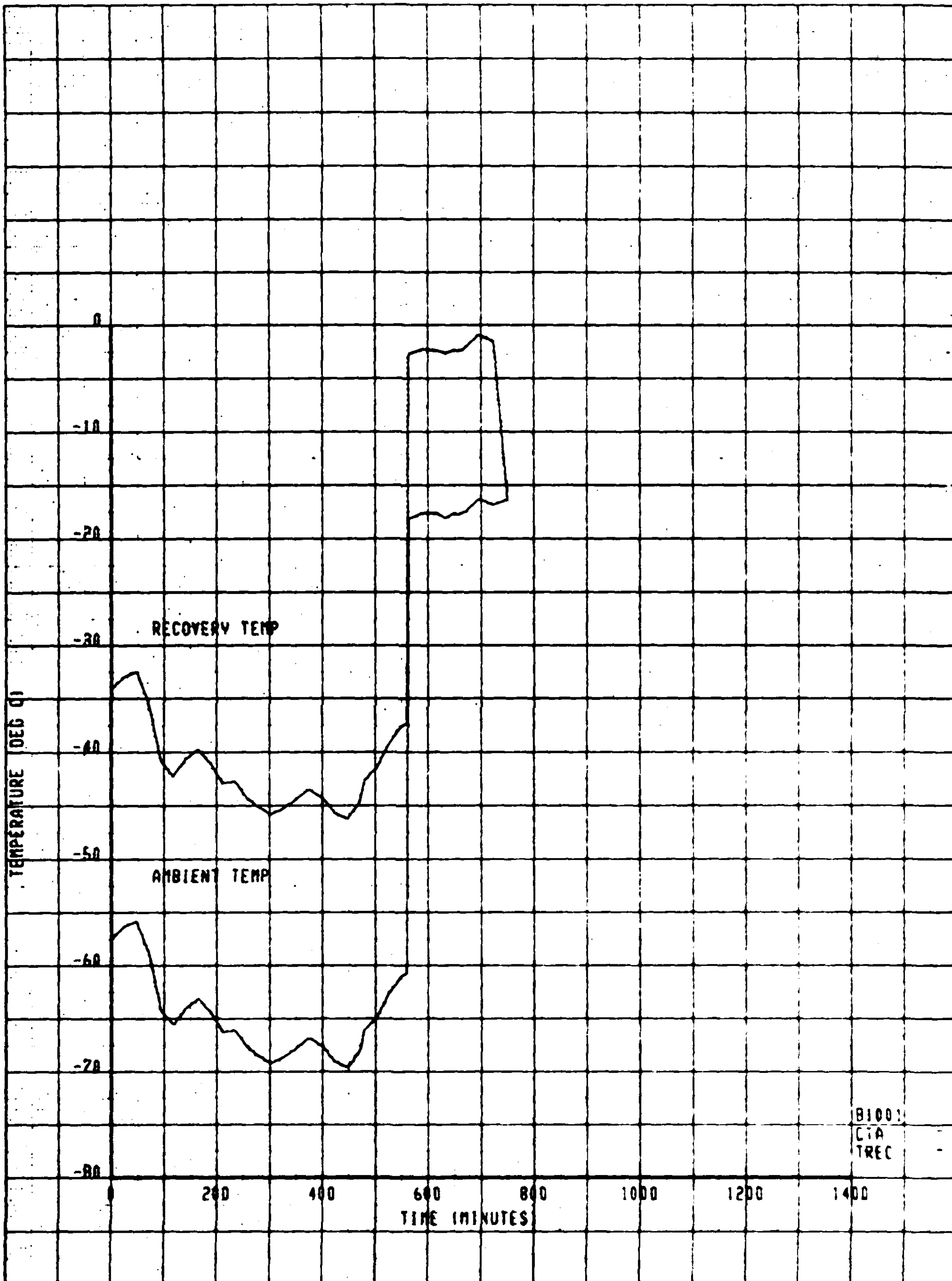

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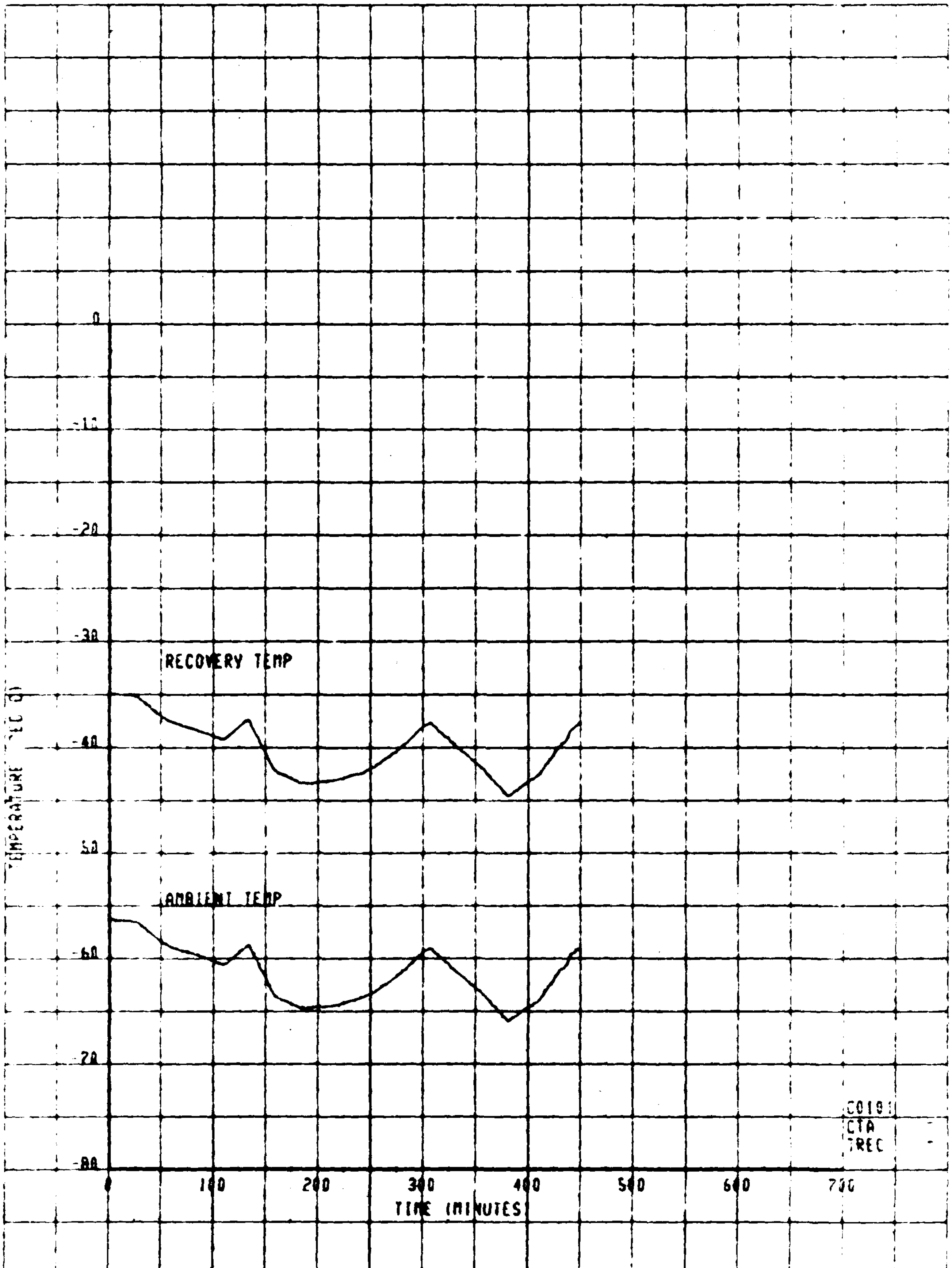
Figure C-40

PAGE C-41



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C-141 DATA
TRACK 1
WORST CASE COLD DAY

THE BOEING COMPANY

Figure C-41

PAGE C-42

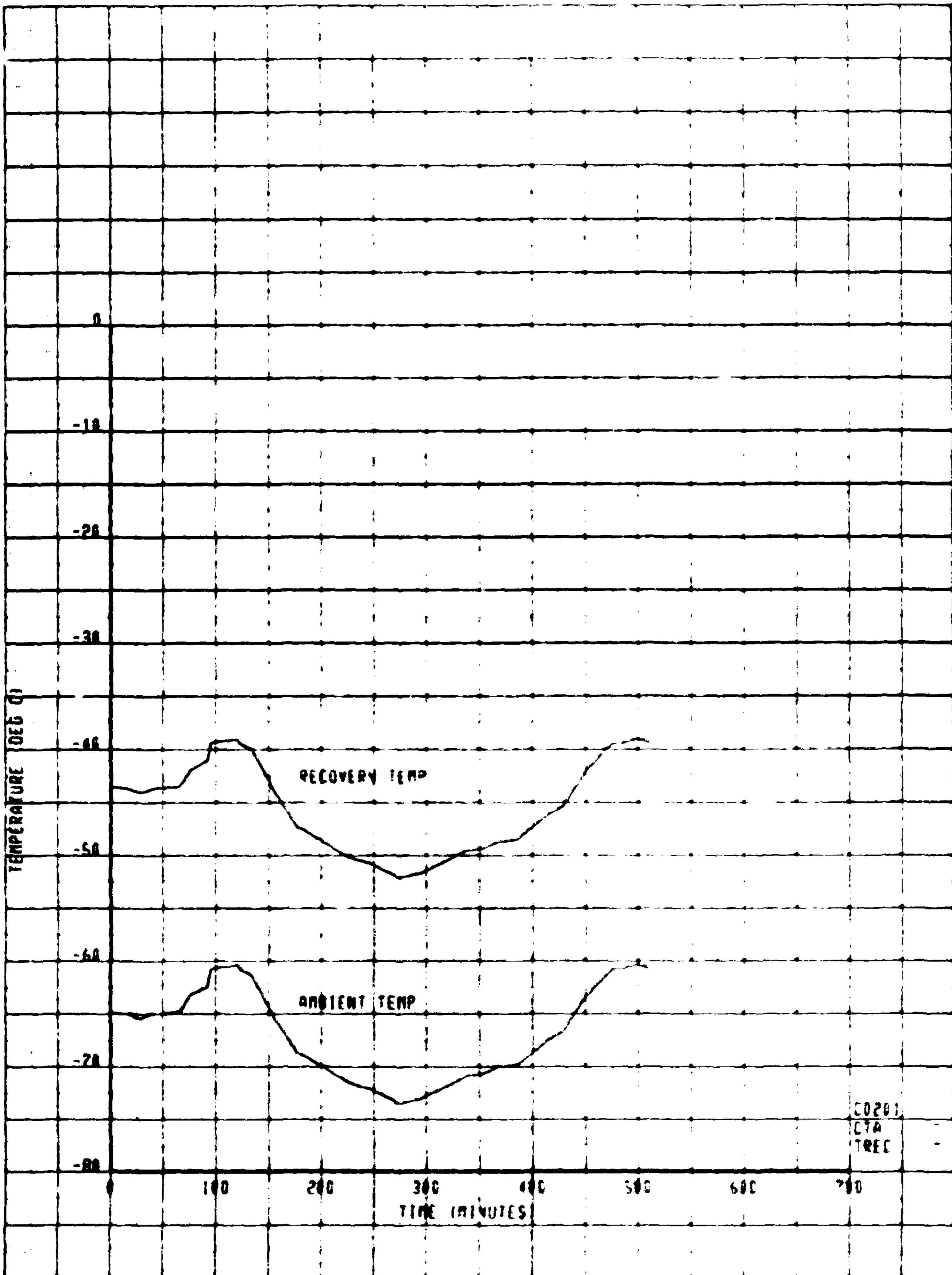

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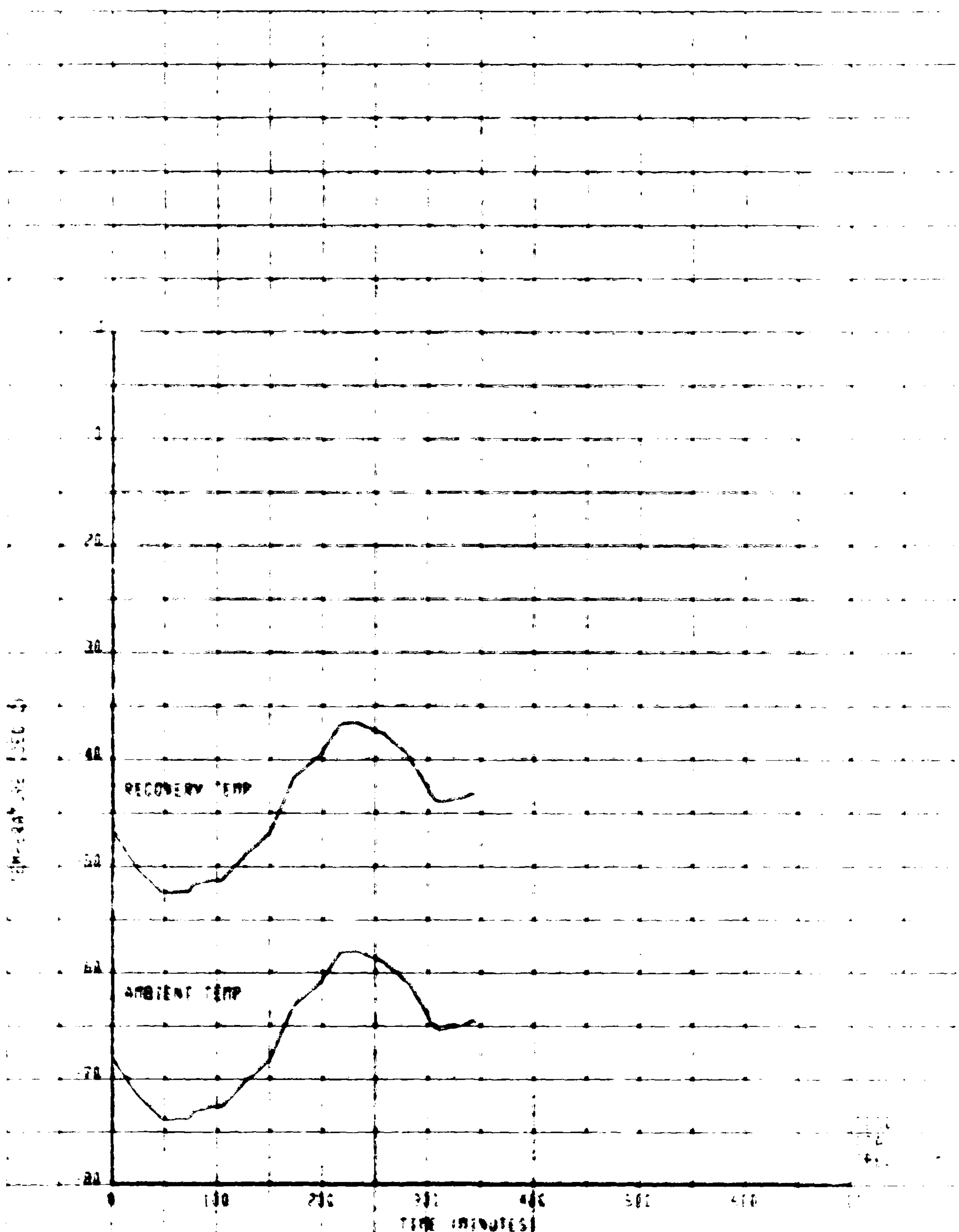
Figure C-42

PAGE C-43



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THE BOEING COMPANY

Figure C-43

C-44

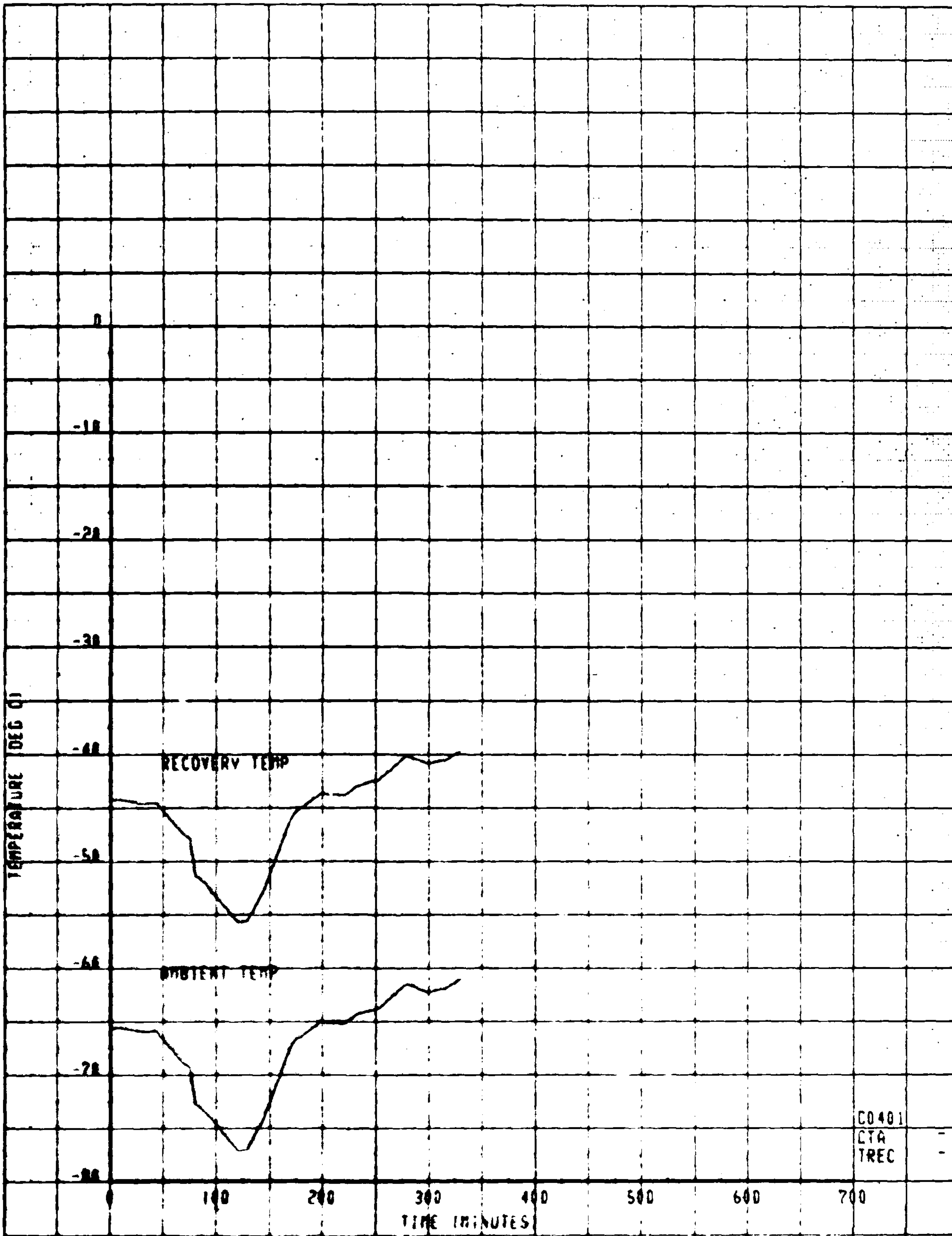

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Figure C-44

PAGE C-45

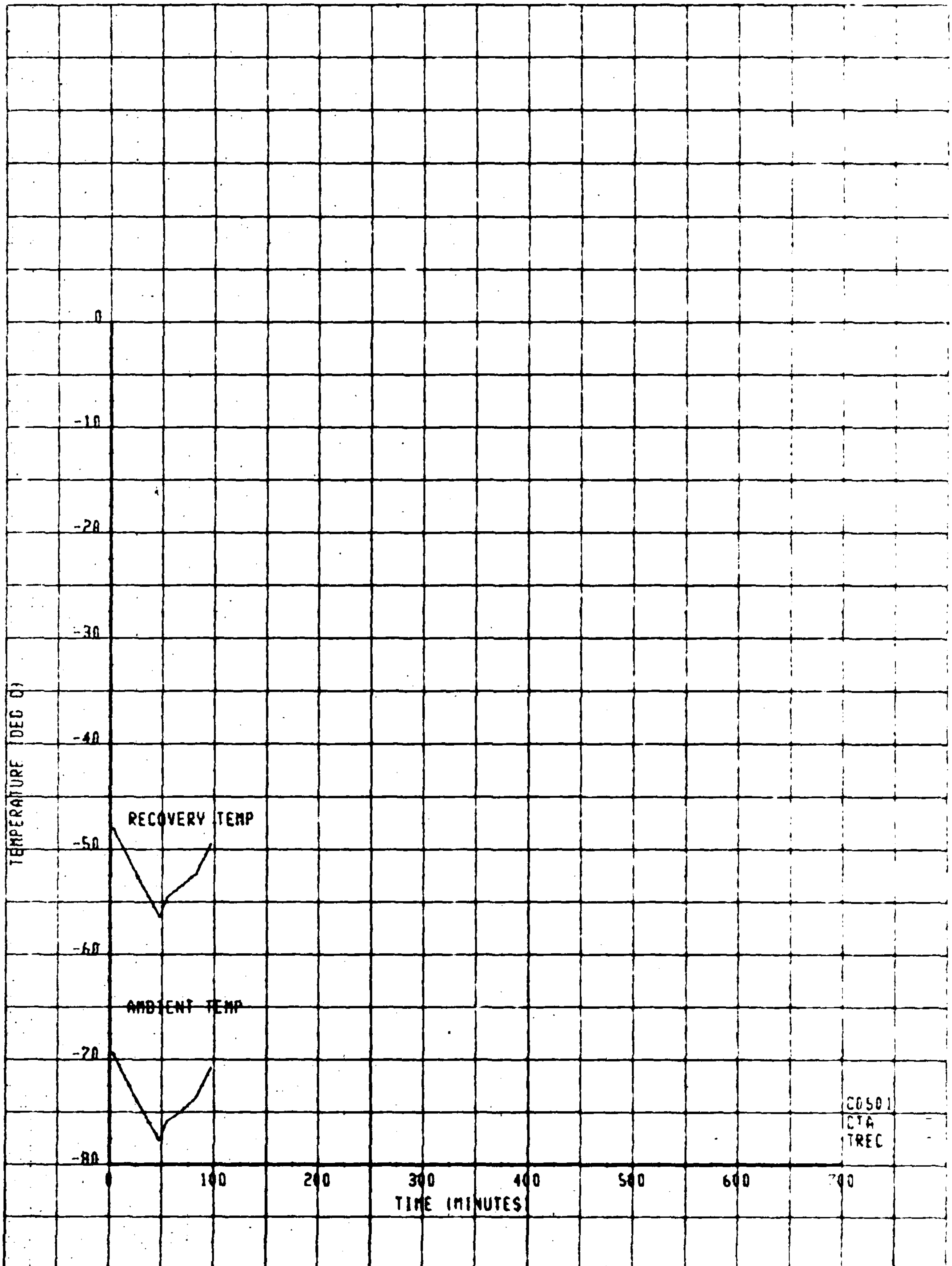

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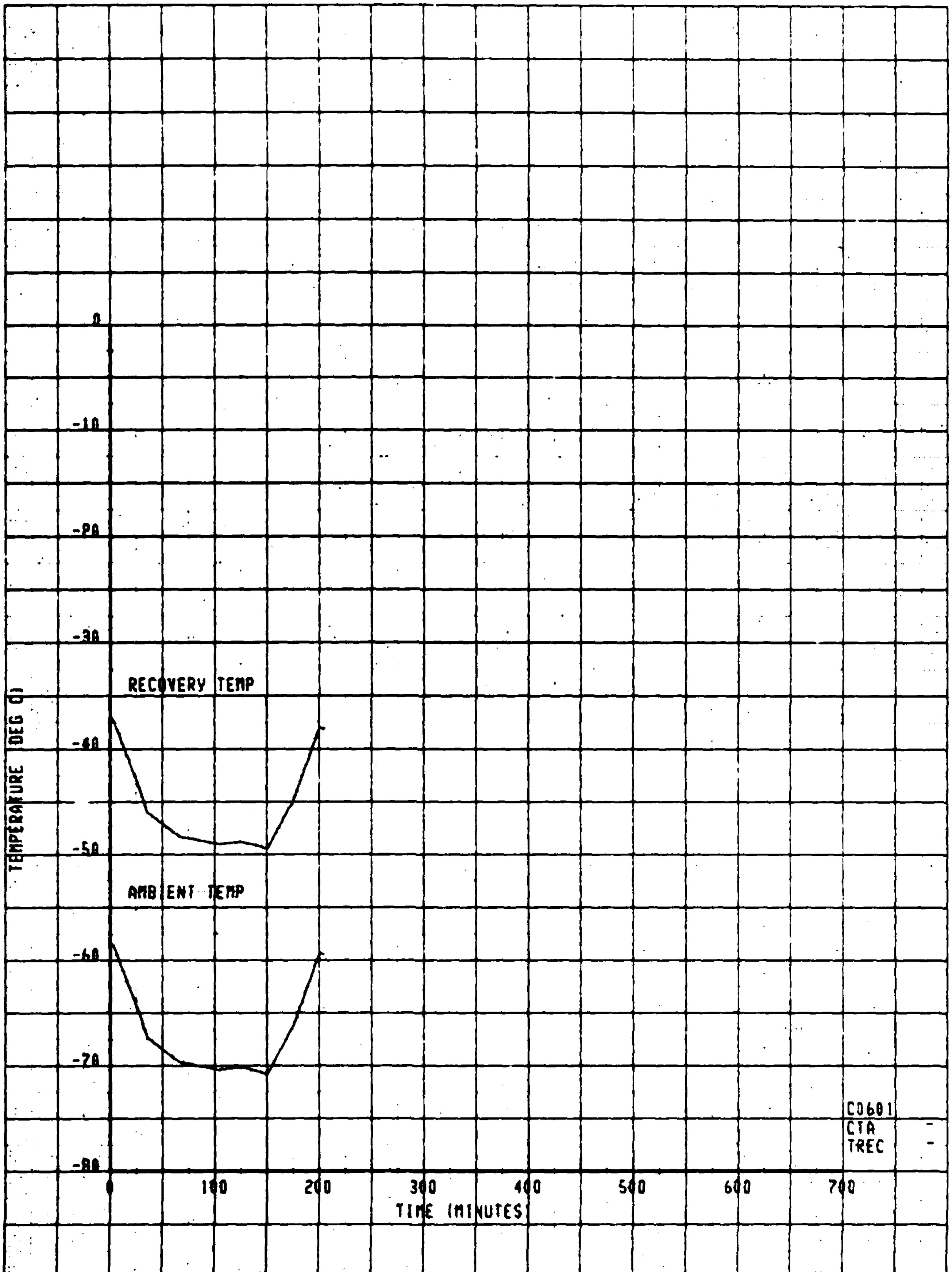
Figure C-45

PAGE C-46



CALC		19AUG81	REVISED	DATE	C-141 DATA TRACK 6 WORST CASE COLD DAY	Figure C-46
CHECK						
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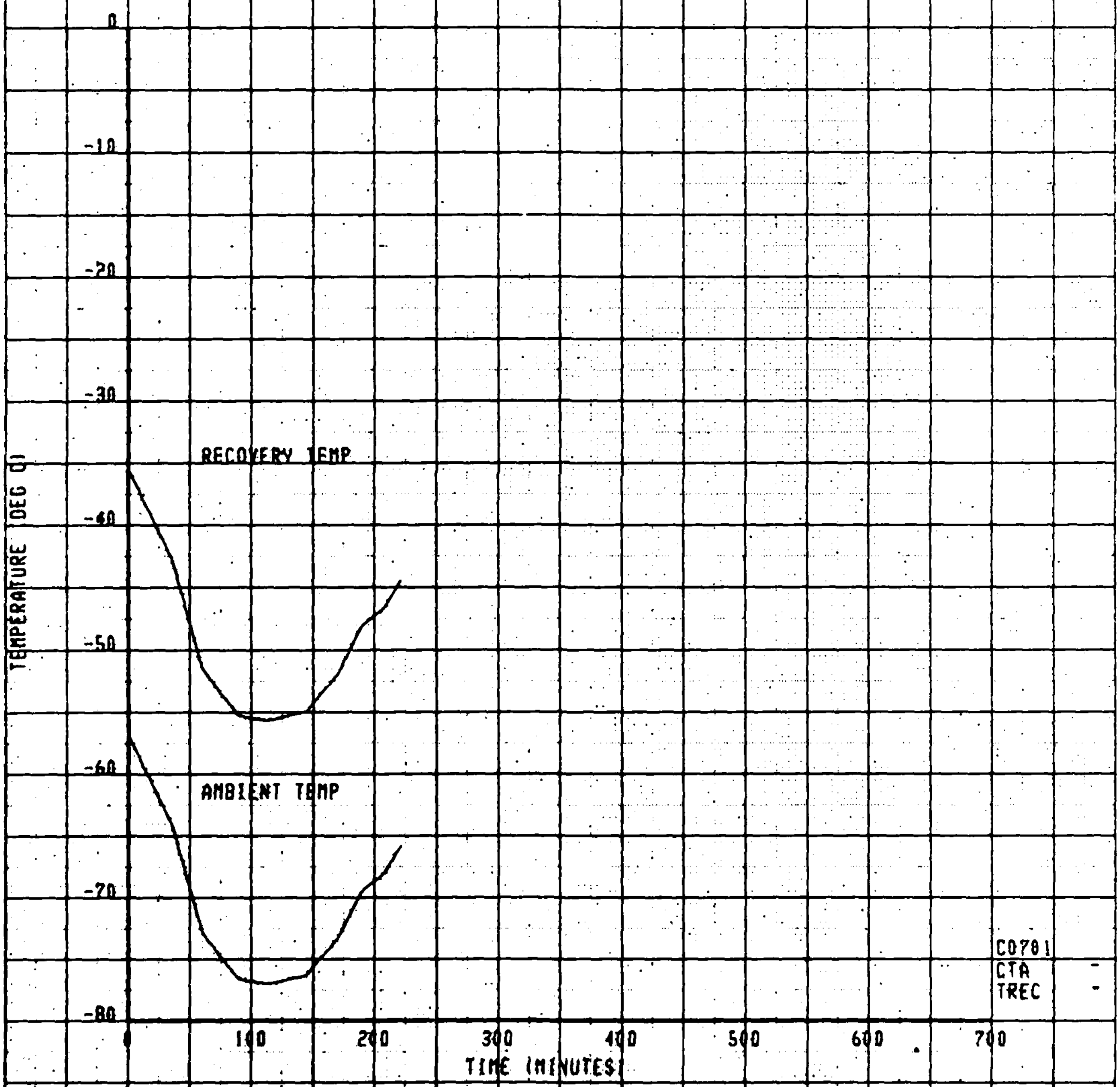
APPD.					THE BOEING COMPANY	PAGE C-47



CALC		19AUG81	REVISED	DATE	C-141 DATA TRACK 7 WORST CASE COLD DAY	Figure C-47
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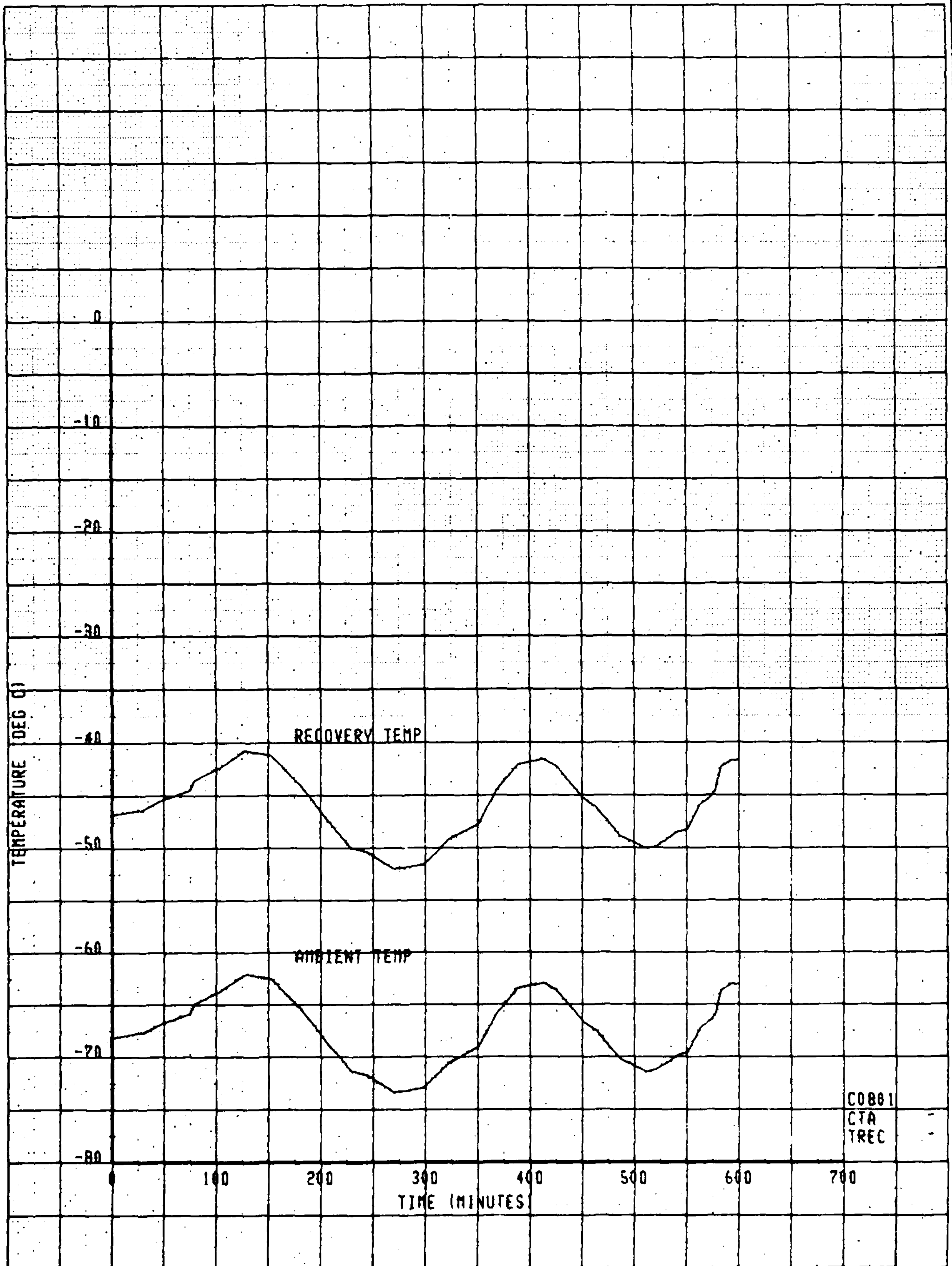

CALC		19AUG81	REVISED	DATE	C-141 DATA TRACK 8 WORST CASE COLD DAY	Figure C-48
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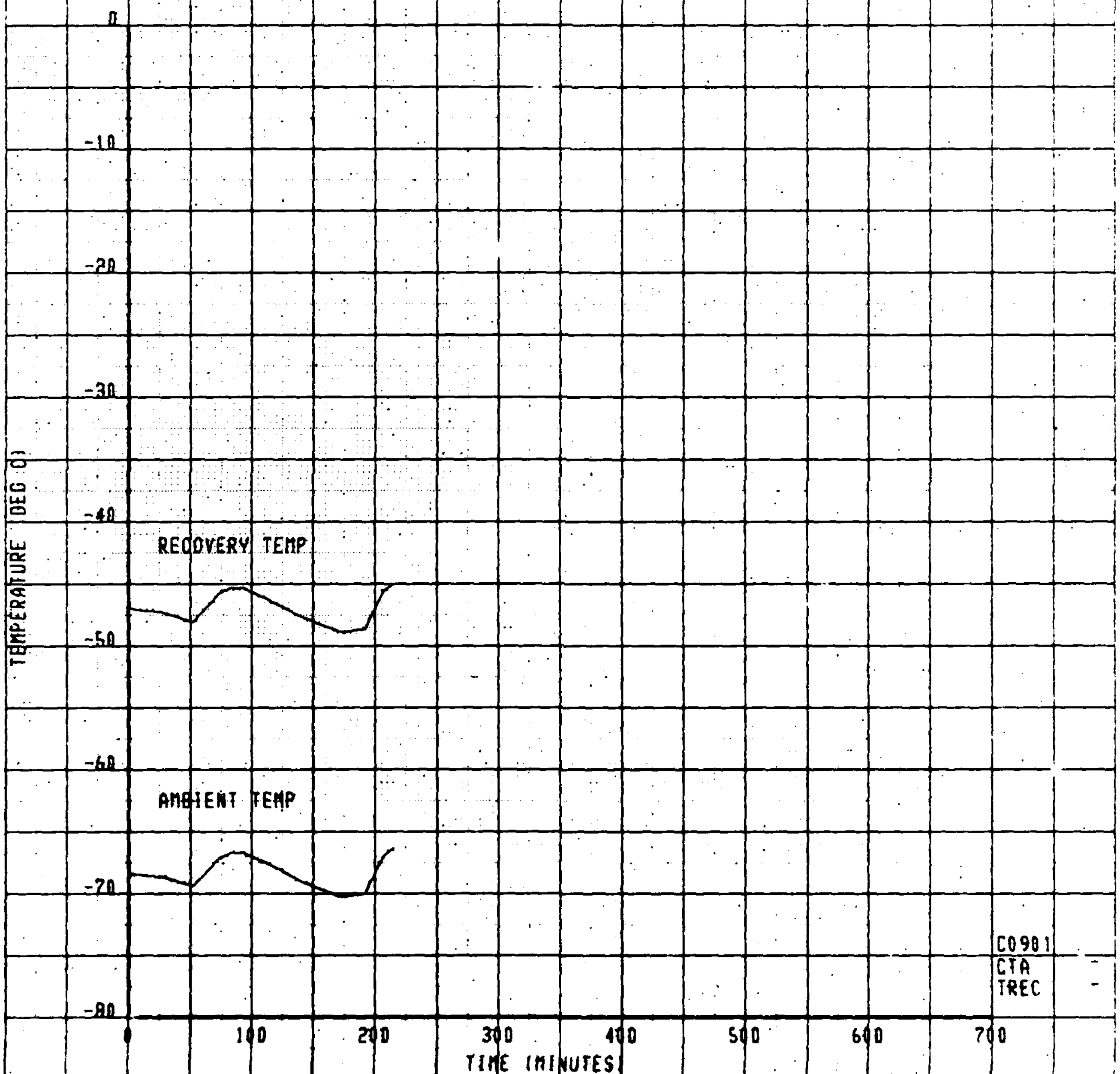
APPD.					THE BOEING COMPANY	PAGE C-49



CALC		19AUG81	REVISED	DATE
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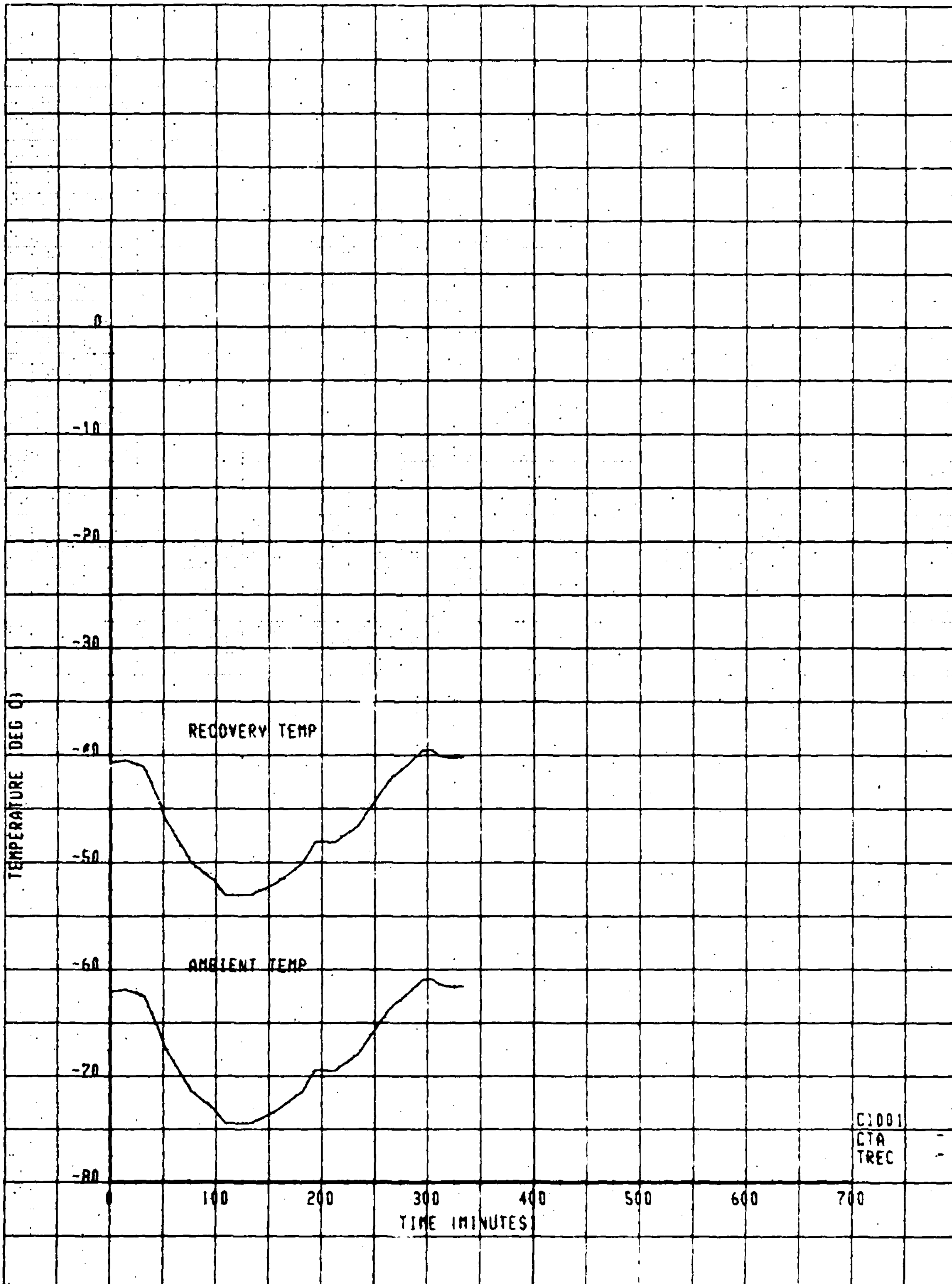
C-141 DATA
TRACK 9
WORST CASE COLD DAY

THE BOEING COMPANY

Figure C-49

PAGE C-50



CALC		19AUG81	REVISED	DATE
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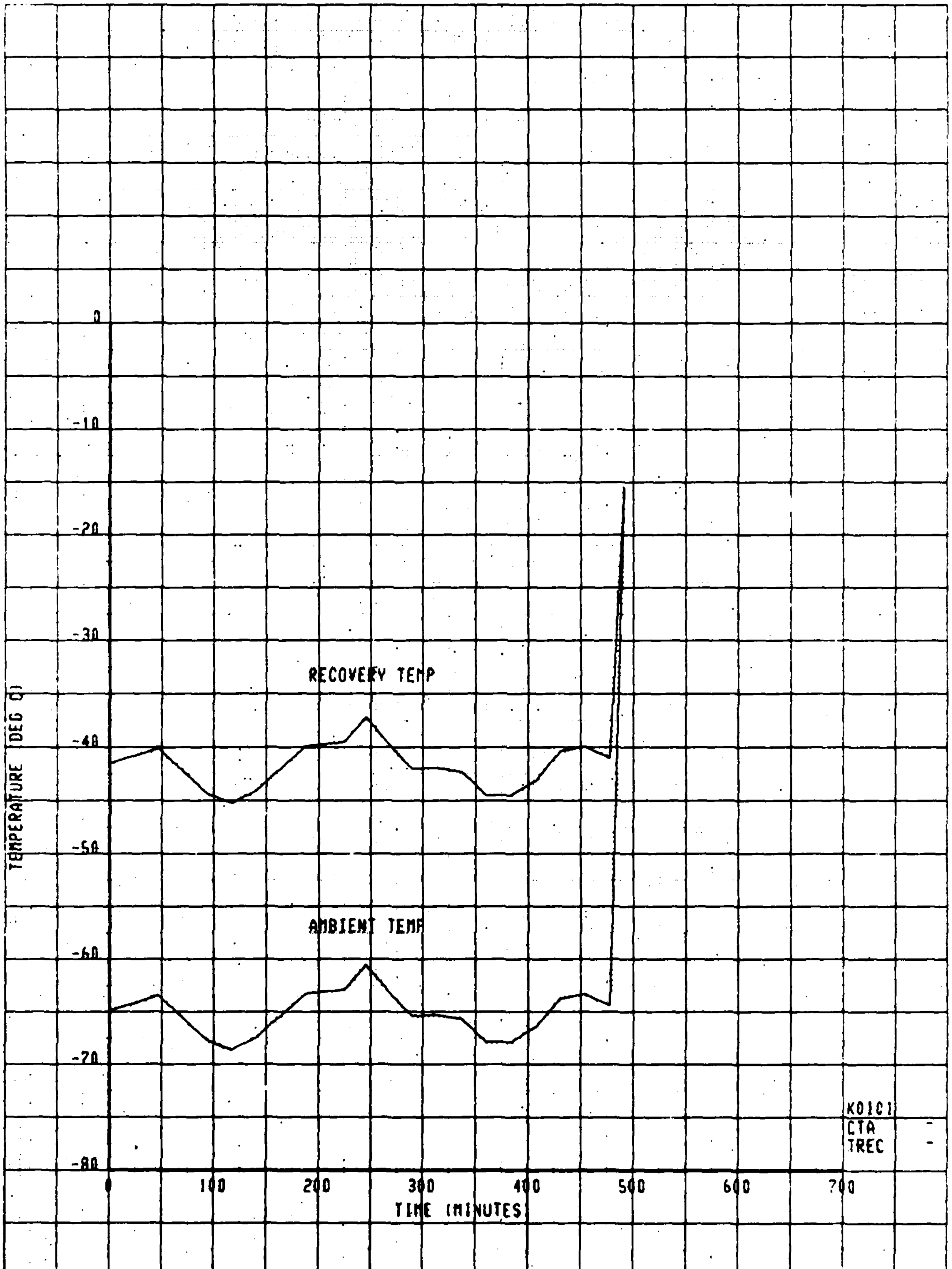
C-141 DATA
RACK 10
WORST CASE COLD DAY

THE BOEING COMPANY

Figure C-50

PAGE C-51



CALC		19AUG81	REVISED	DATE
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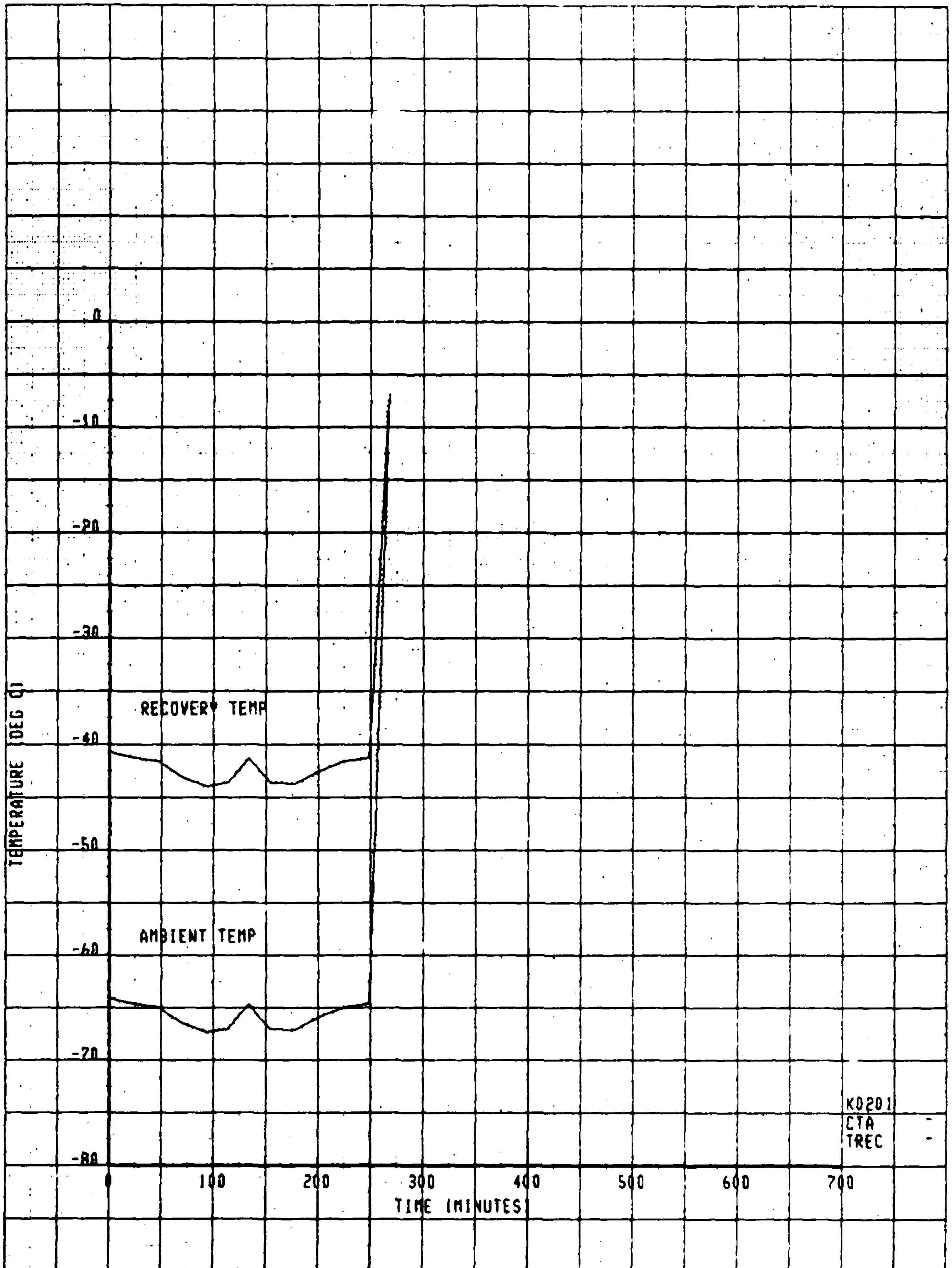
KC-135 DATA
TRACK 1
WORST CASE COLD DAY

THE BOEING COMPANY

Figure C-51

PAGE C-52



CALC		19AUG81	REVISED	DATE	KC-135 DATA TRACK 2 WORST CASE COLD DAY	Figure C-52
CHECK						
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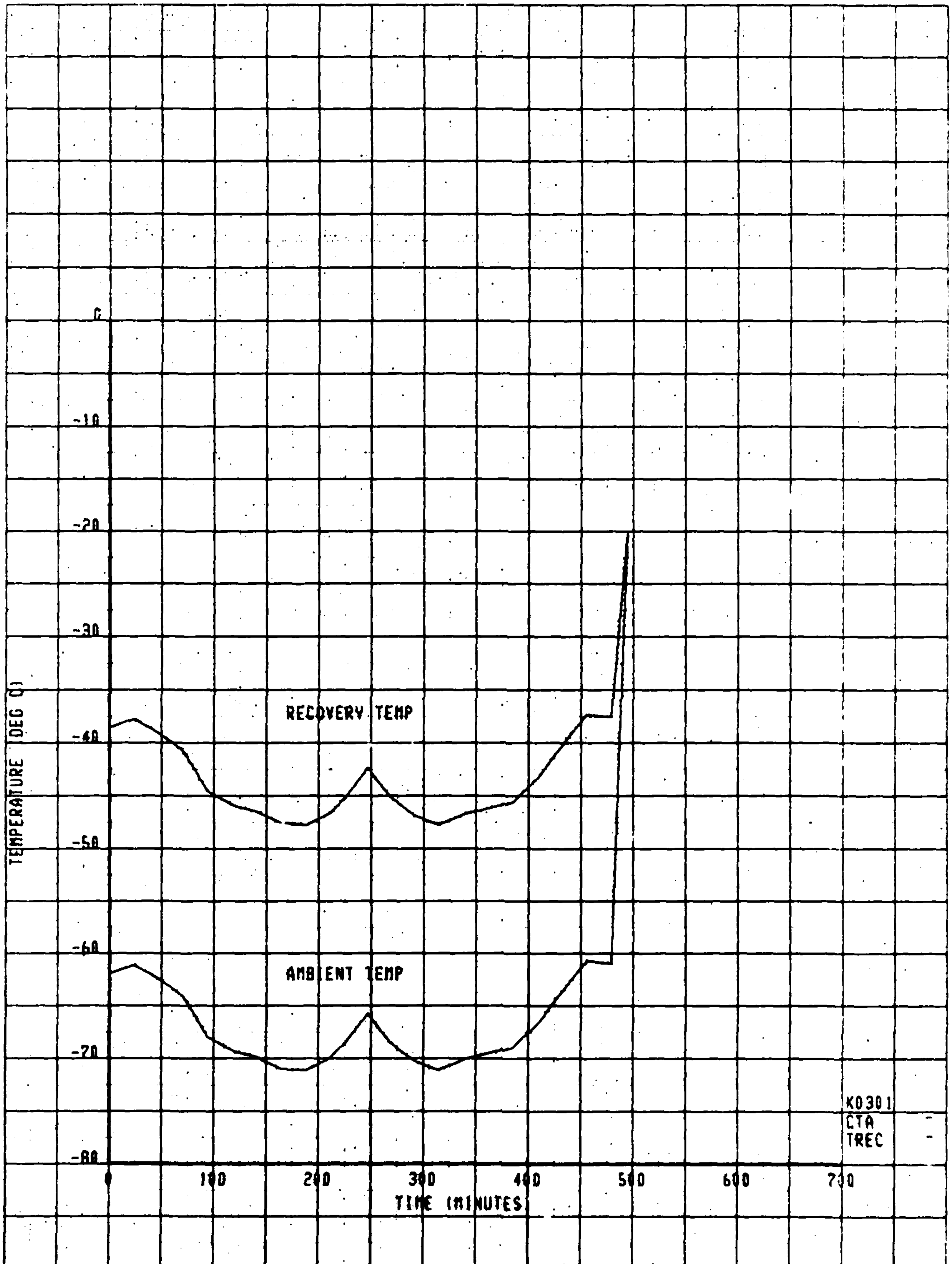
APPD.					THE BOEING COMPANY	PAGE C-53



CALC		19AUG81	REVISED	DATE	KC-135 DATA TRACK 3 WORST CASE COLD DAY	Figure C-53
CHECK						
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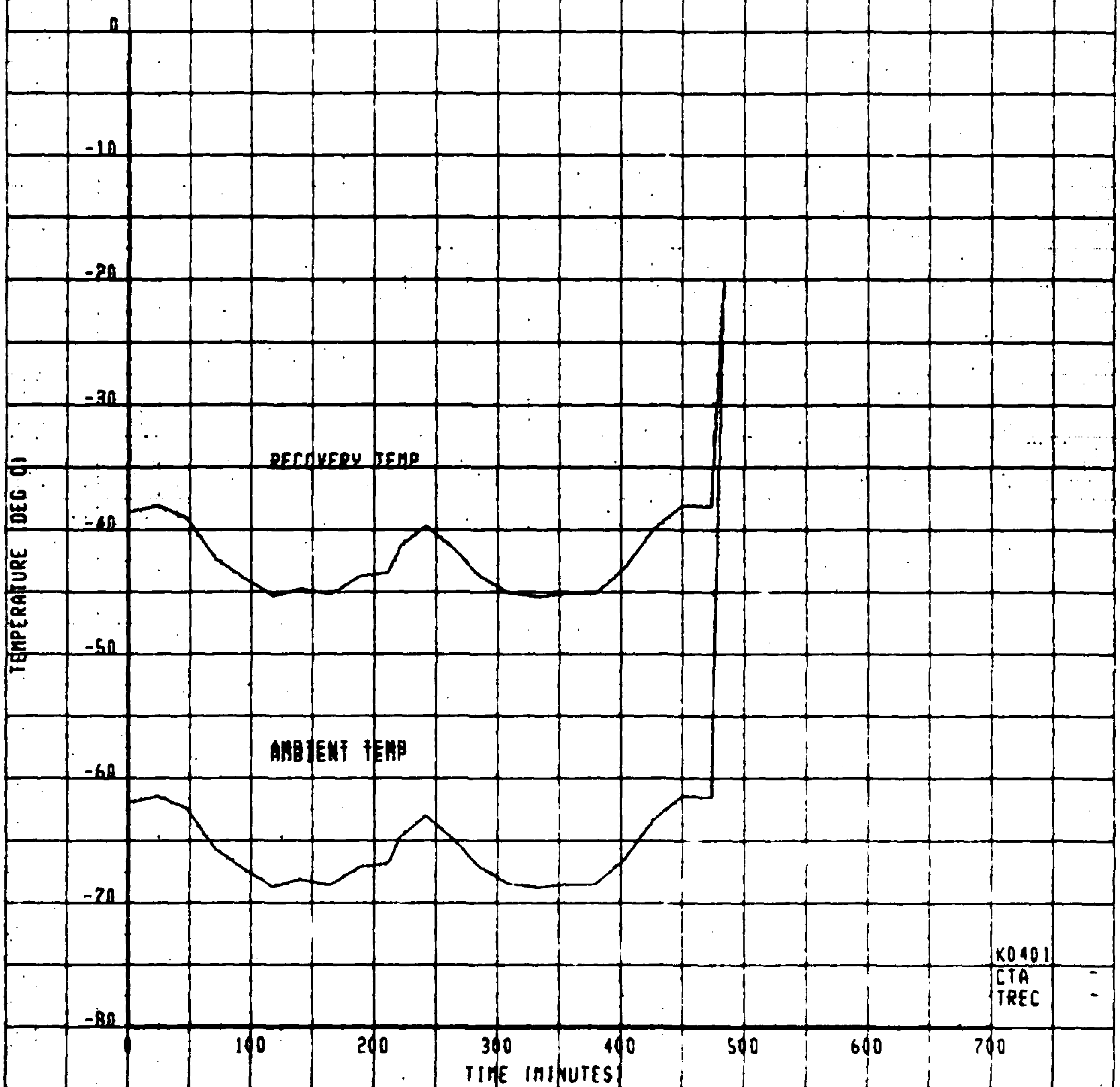
APPD.					THE BOEING COMPANY	PAGE C-54



CALC		19AUG81	REVISED	DATE	KC-135 DATA TRACK 4 WORST CASE COLD DAY
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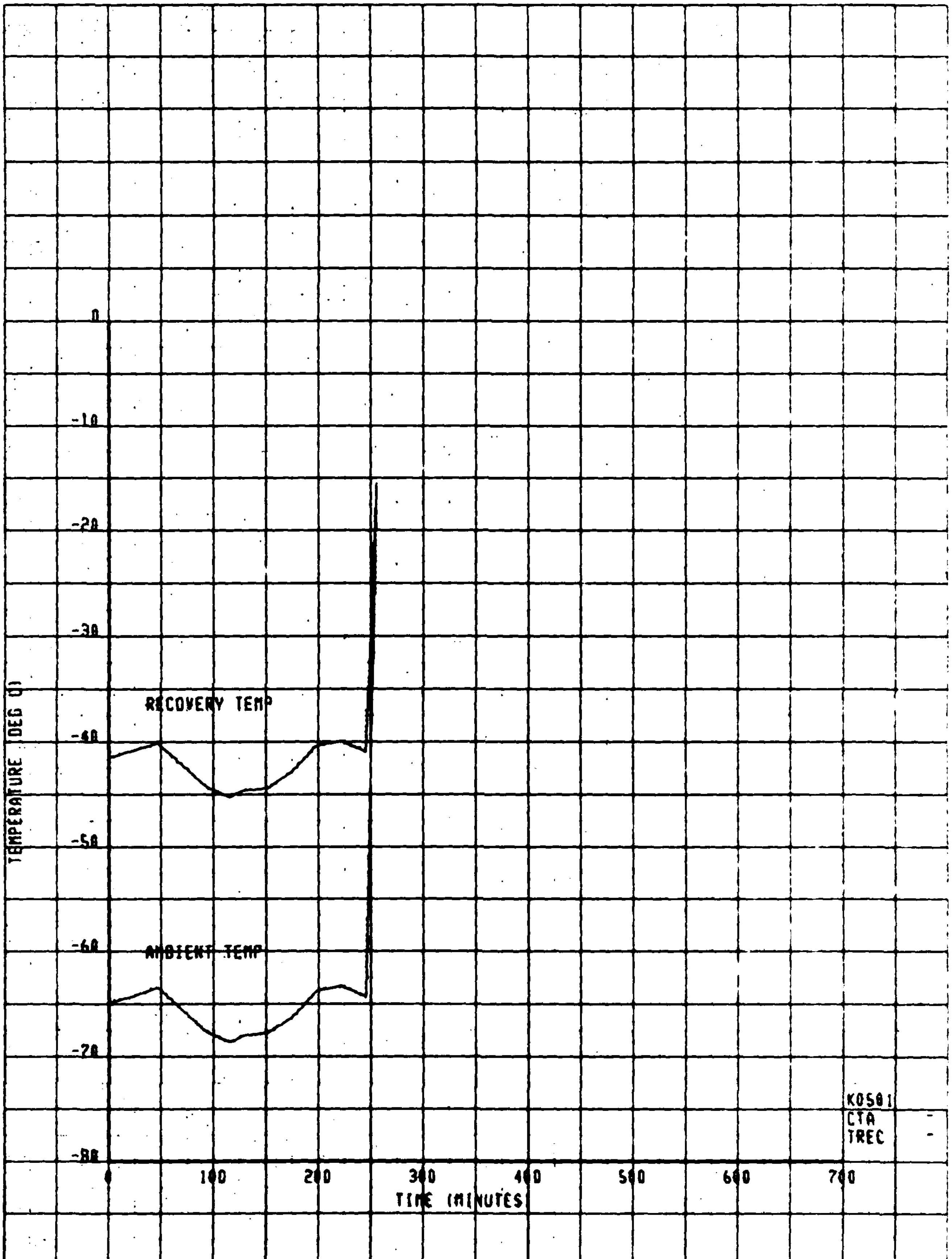
APPD.					THE BOEING COMPANY
					PAGE C-55



CALC		15DEC81	REVISED	DATE	KC-135 DATA TRACK 5 WORST CASE COLD DAY
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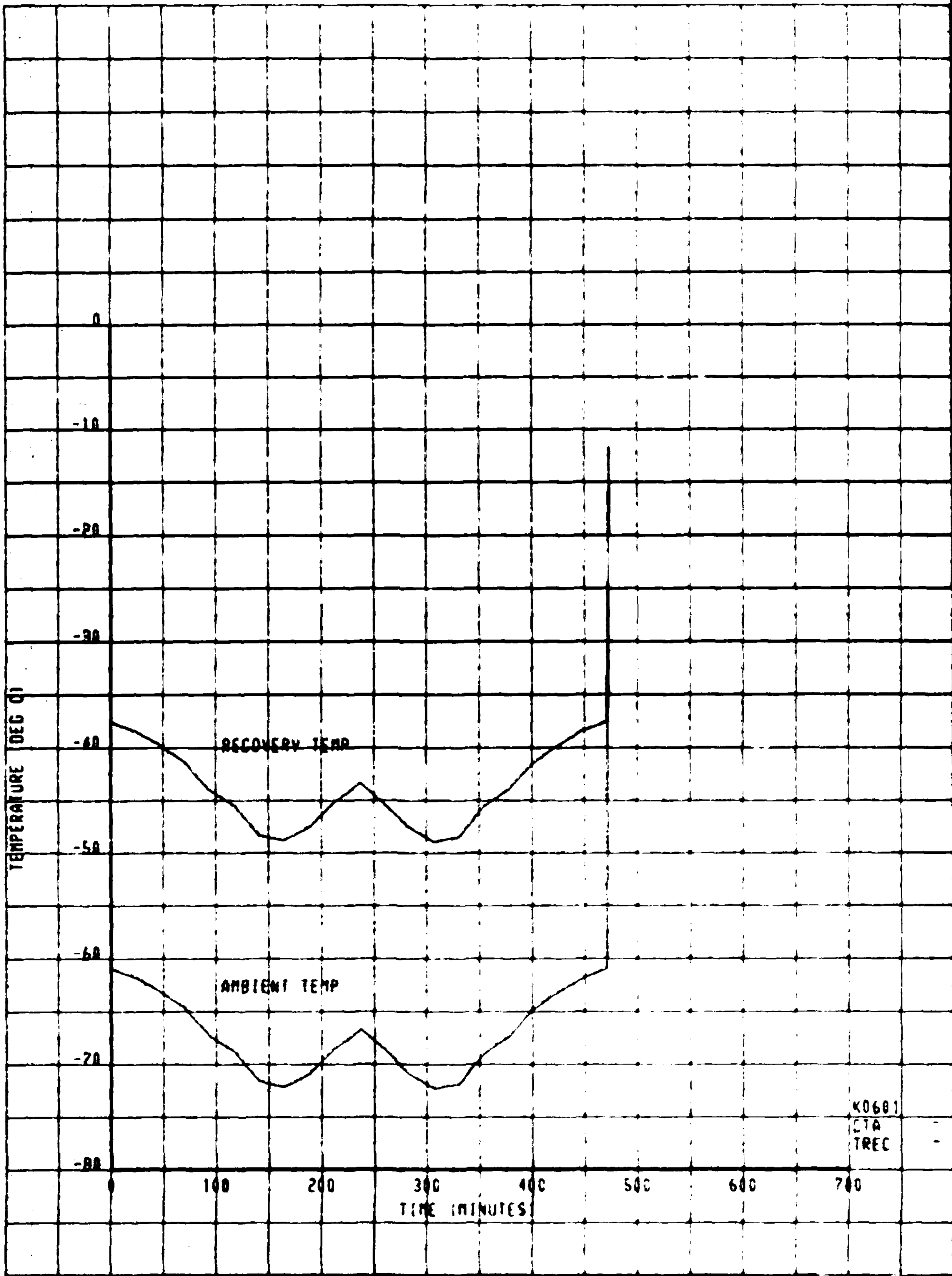
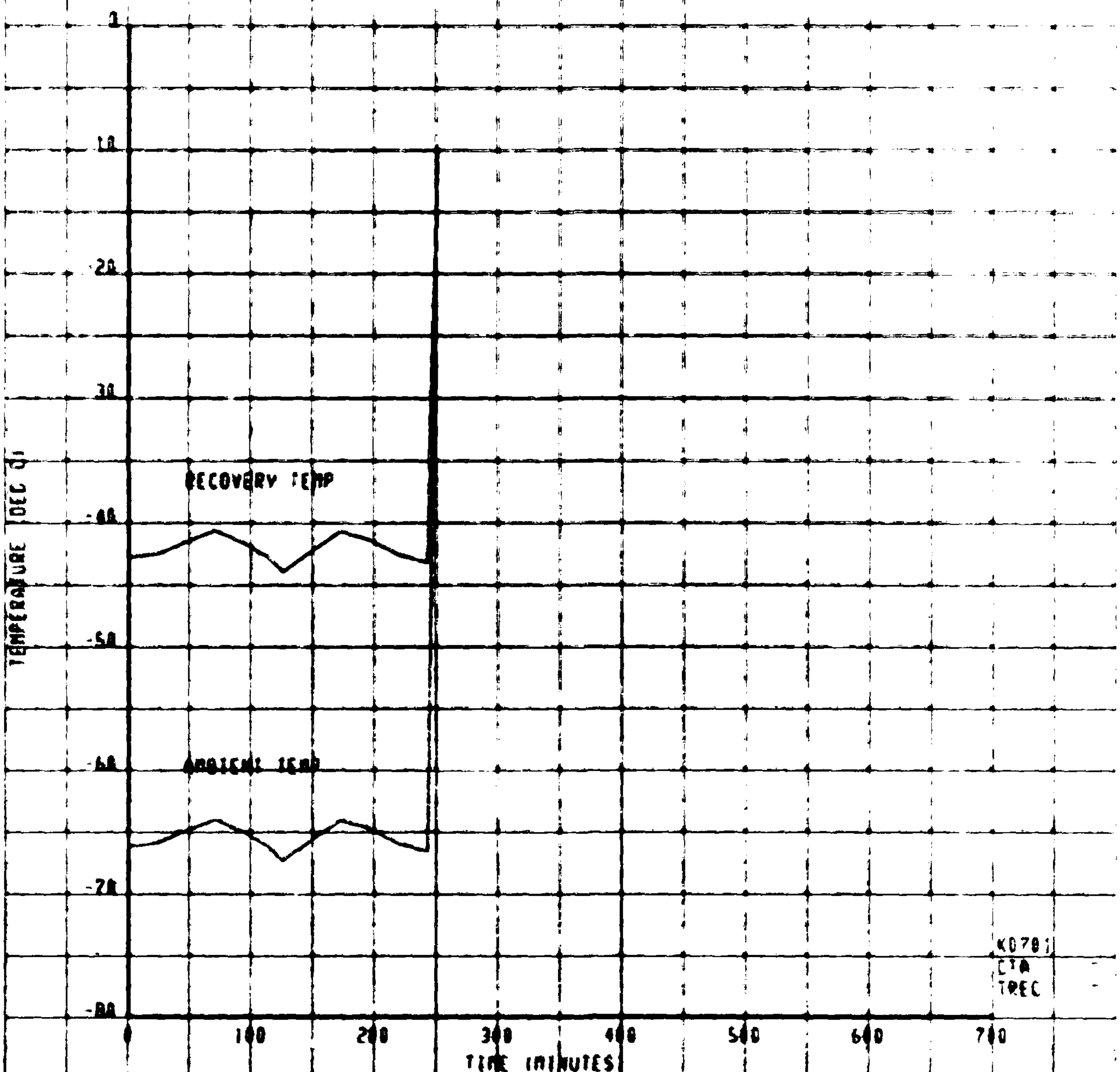
Figure C-56

PAGE C-56



CALC		15DEC81	REVISED	DATE	KC-135 DATA	Figure C-56
CHECK				15DEC81	TRACK 6	
APPD.					WORST CASE COLD DAY	
APPD.					THE BOEING COMPANY	PAGE C-57



CALC		SOEC81	REVISED	DATE
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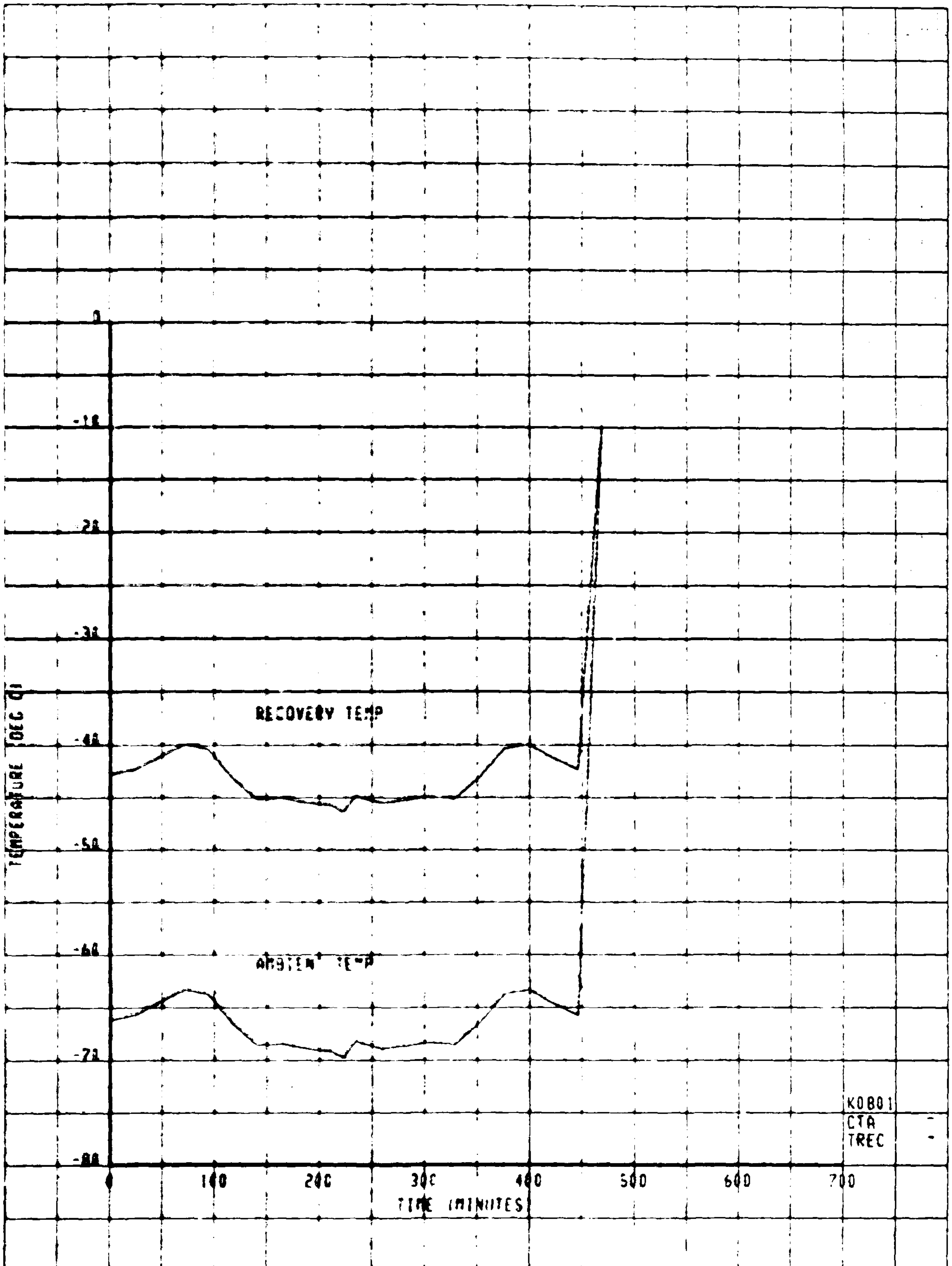
KC-135 DATA
TRACK 7
WORST CASE COLD DAY

THE BOEING COMPANY

Figure C-67

PAGE C-68



CALC		15DEC81	REVISED	DATE	KC-135 DATA TRACK 8 WORST CASE COLD DAY	Figure C-58
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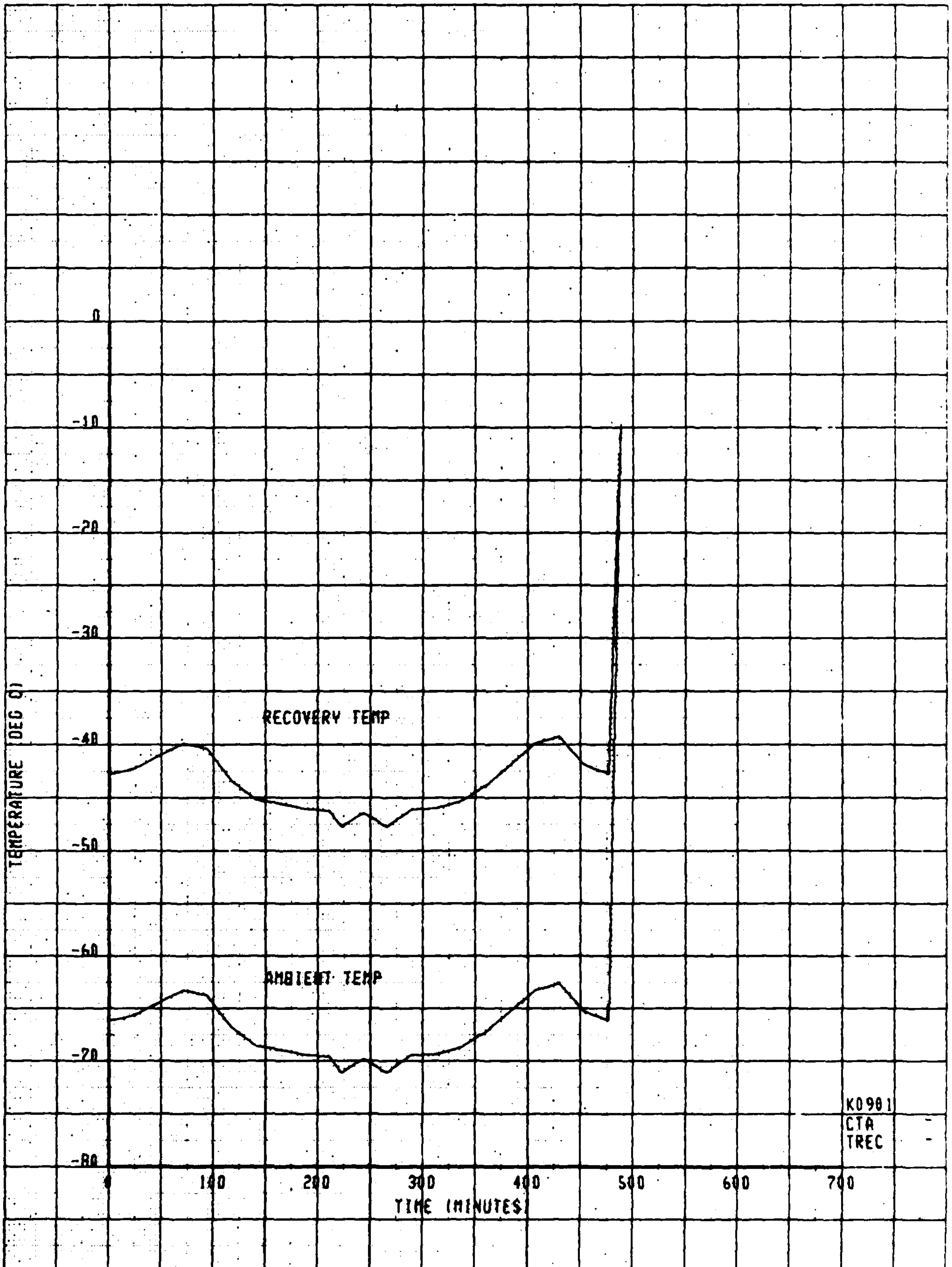
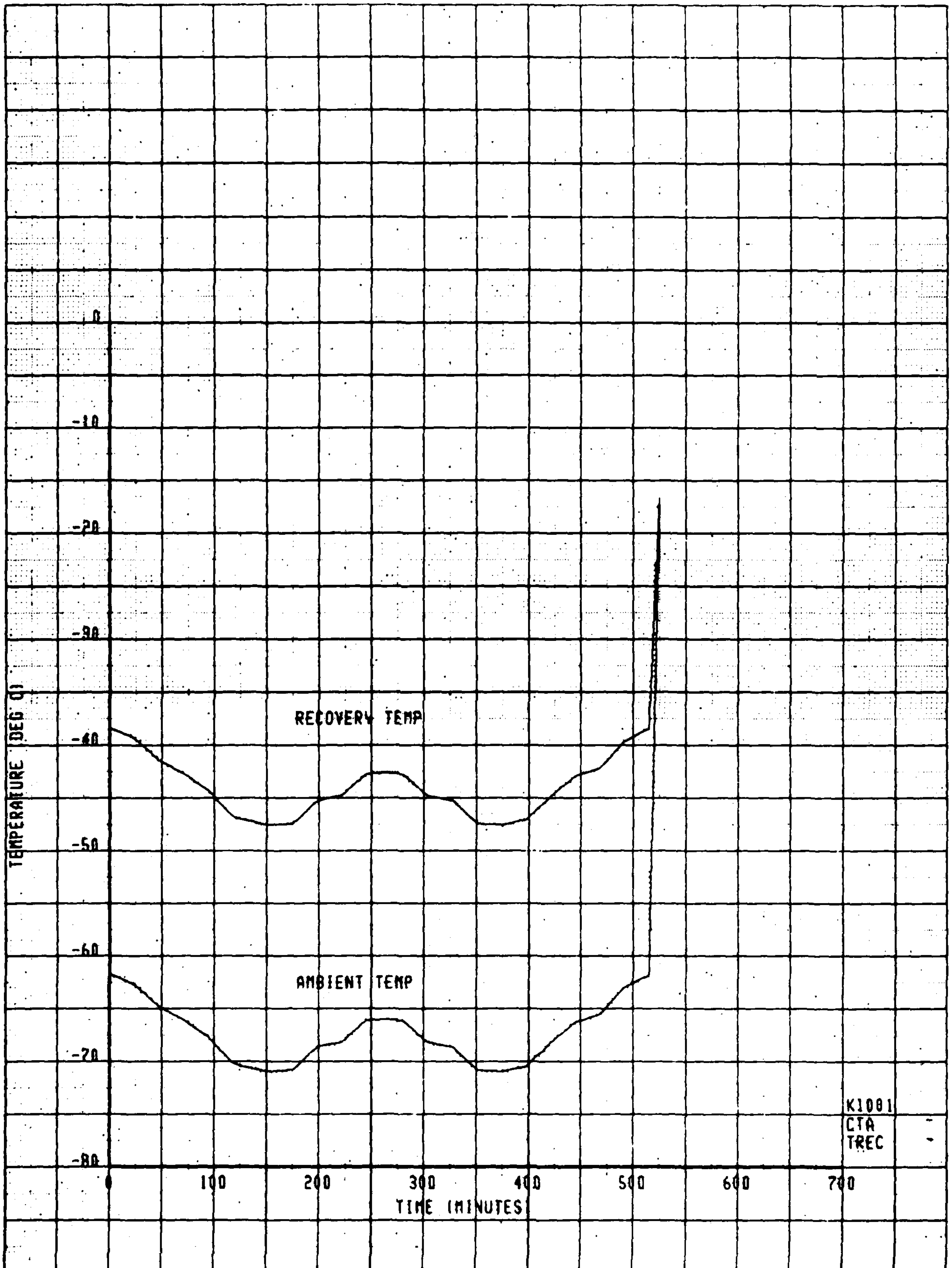
APPD.					THE BOEING COMPANY	PAGE C-59



CALC		19AUG81	REVISED	DATE	KC-135 DATA	Figure C-59
CHECK					TRACK 9	
APPD.					WORST CASE COLD DAY	
APPD.					THE BOEING COMPANY	PAGE C-60



CALC		19AUG81	REVISED	DATE	KC-135 DATA	Figure C-60
CHECK					TRACK 10	
APPD.					WORST CASE COLD DAY	
APPD.					THE BOEING COMPANY	PAGE C-61

APPENDIX D

Predicted top to bottom temperature profiles for C-141 Track 8, KC-135 Track 6, B-52 Track 6, and B-52 Track 10 are shown in this appendix. Within each track, the first figure shows the profile development from the initial condition (the result of preconditioning the fuel prior to takeoff) to mid-mission; the second, and for long flights, the third figure shows further profile development during the mission; the last figure shows details of the profile at the tank bottom at the lowest tank temperatures encountered.

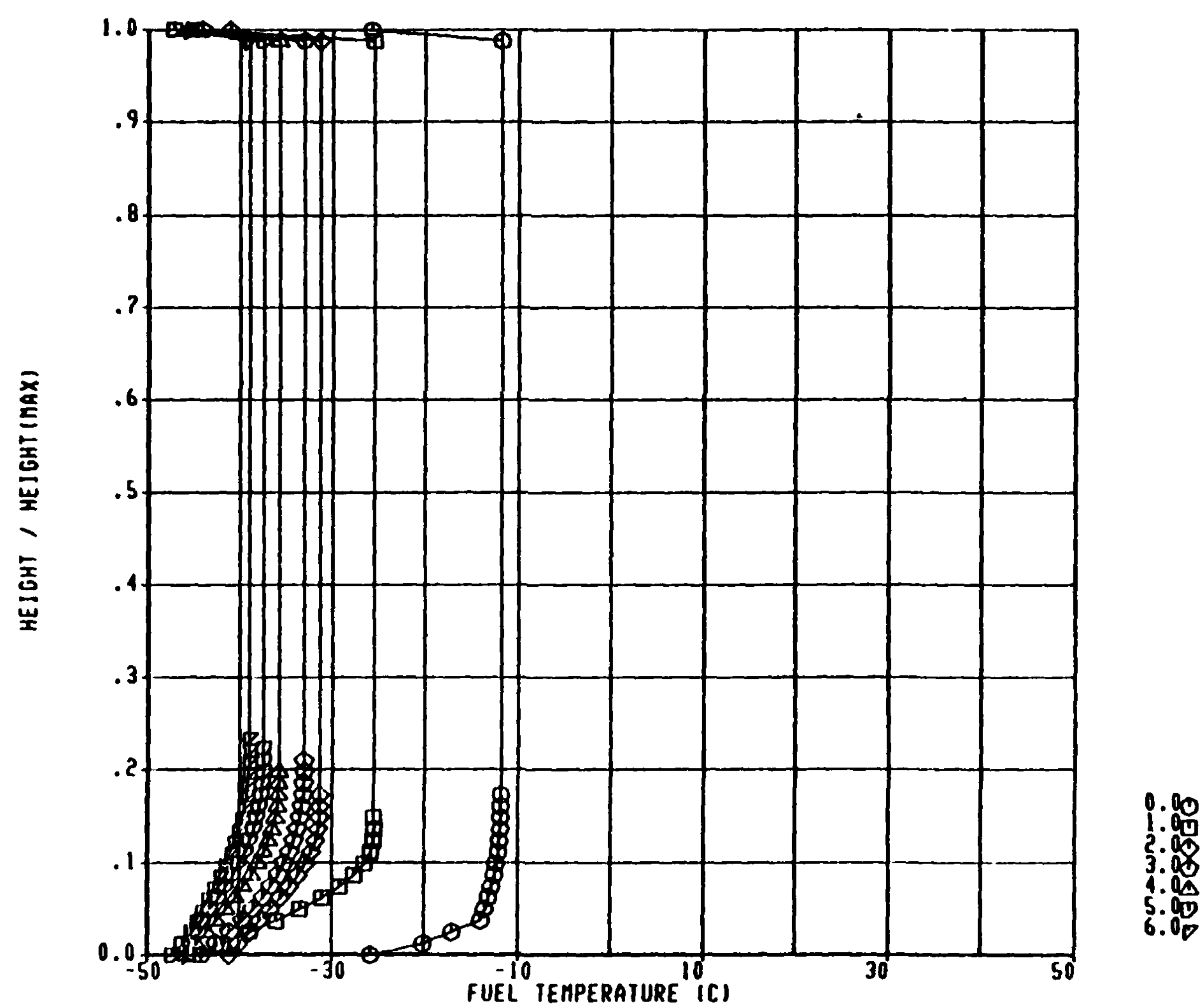


Figure D-1a. Predicted Thermal Profiles C-141, Track 8

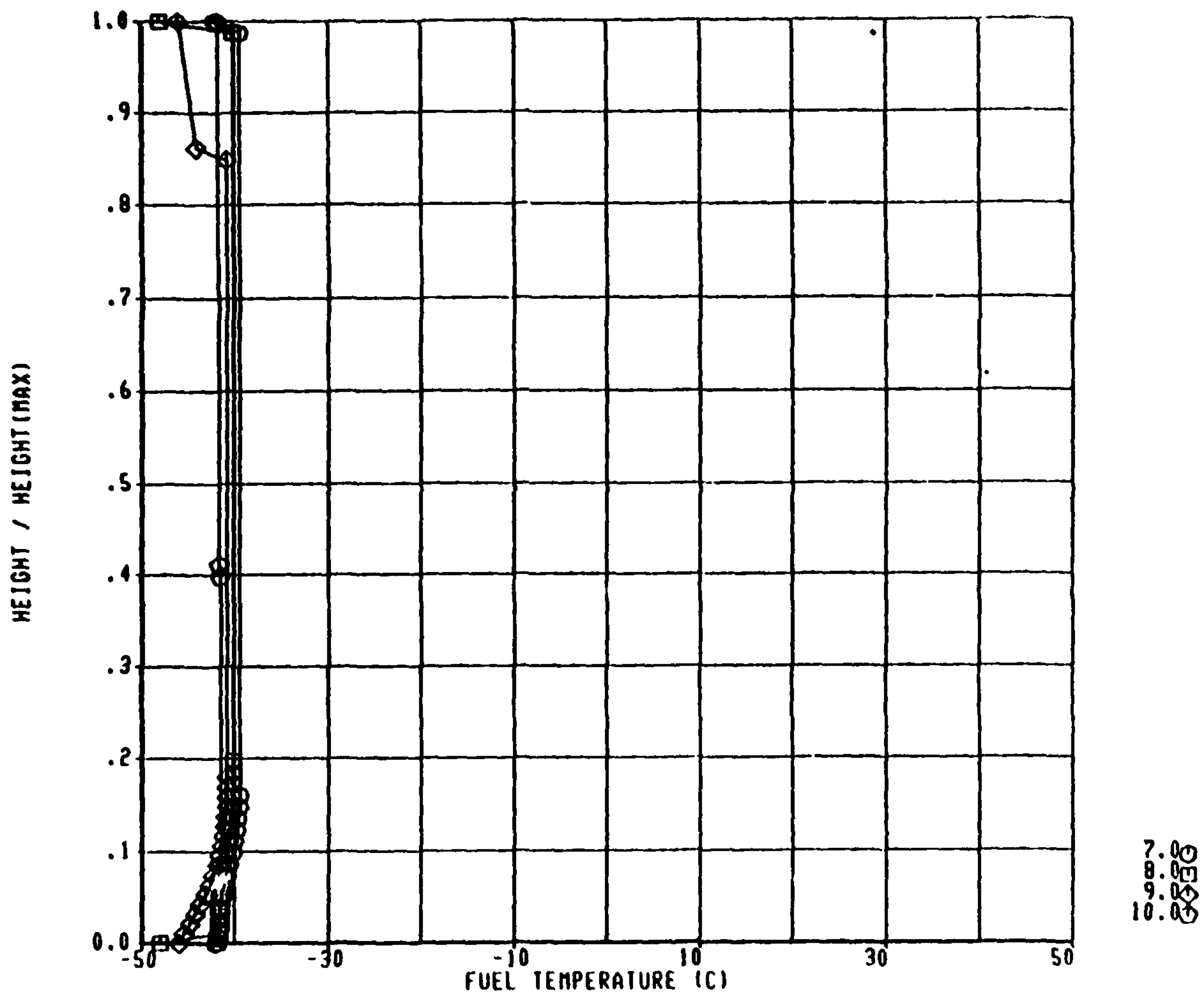


Figure D-1b. Predicted Thermal Profiles C-141, Track 8

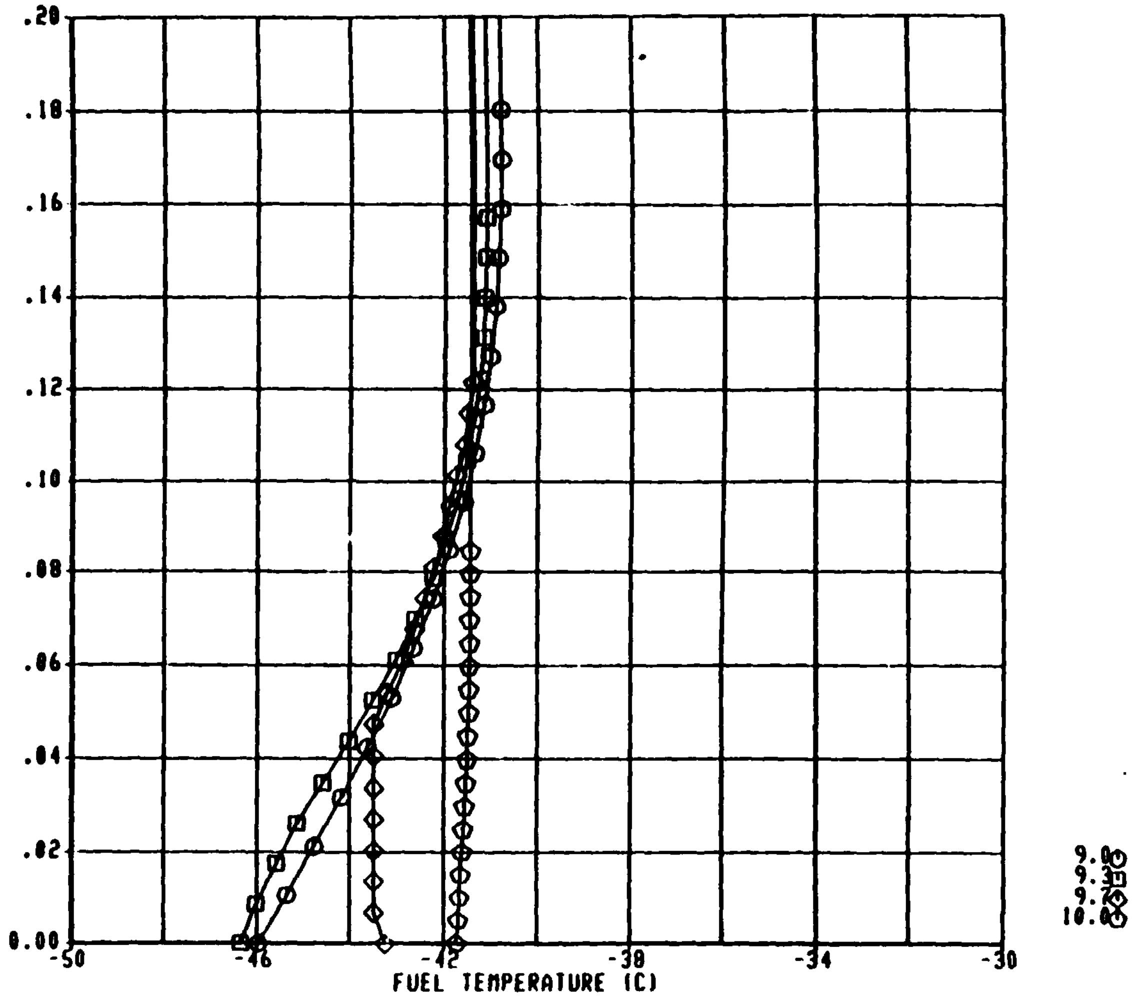


Figure D-1c. Predicted Thermal Profiles C-141, Track 8

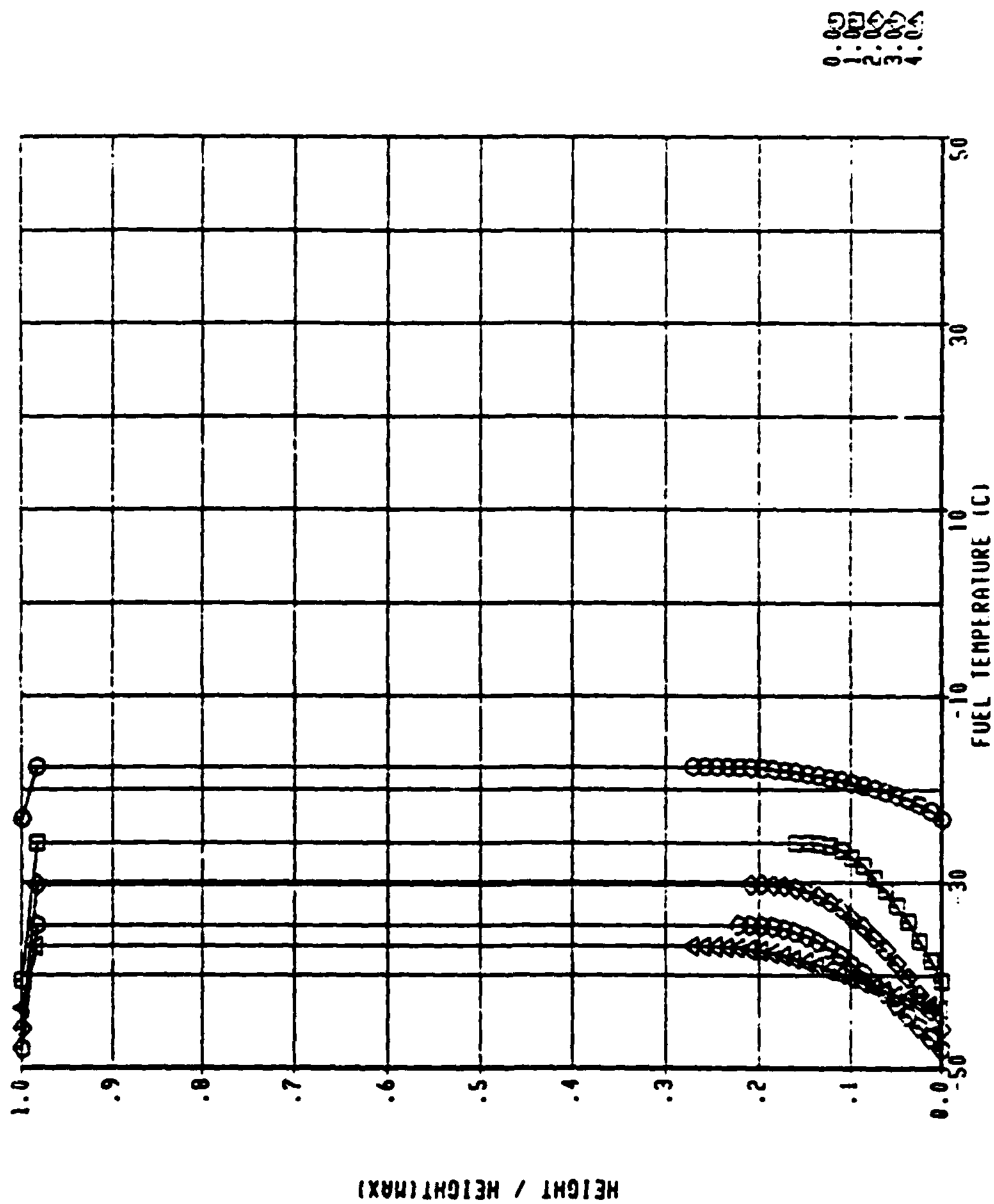


Figure D-2a. Predicted Thermal Profiles KC-135, Track 6

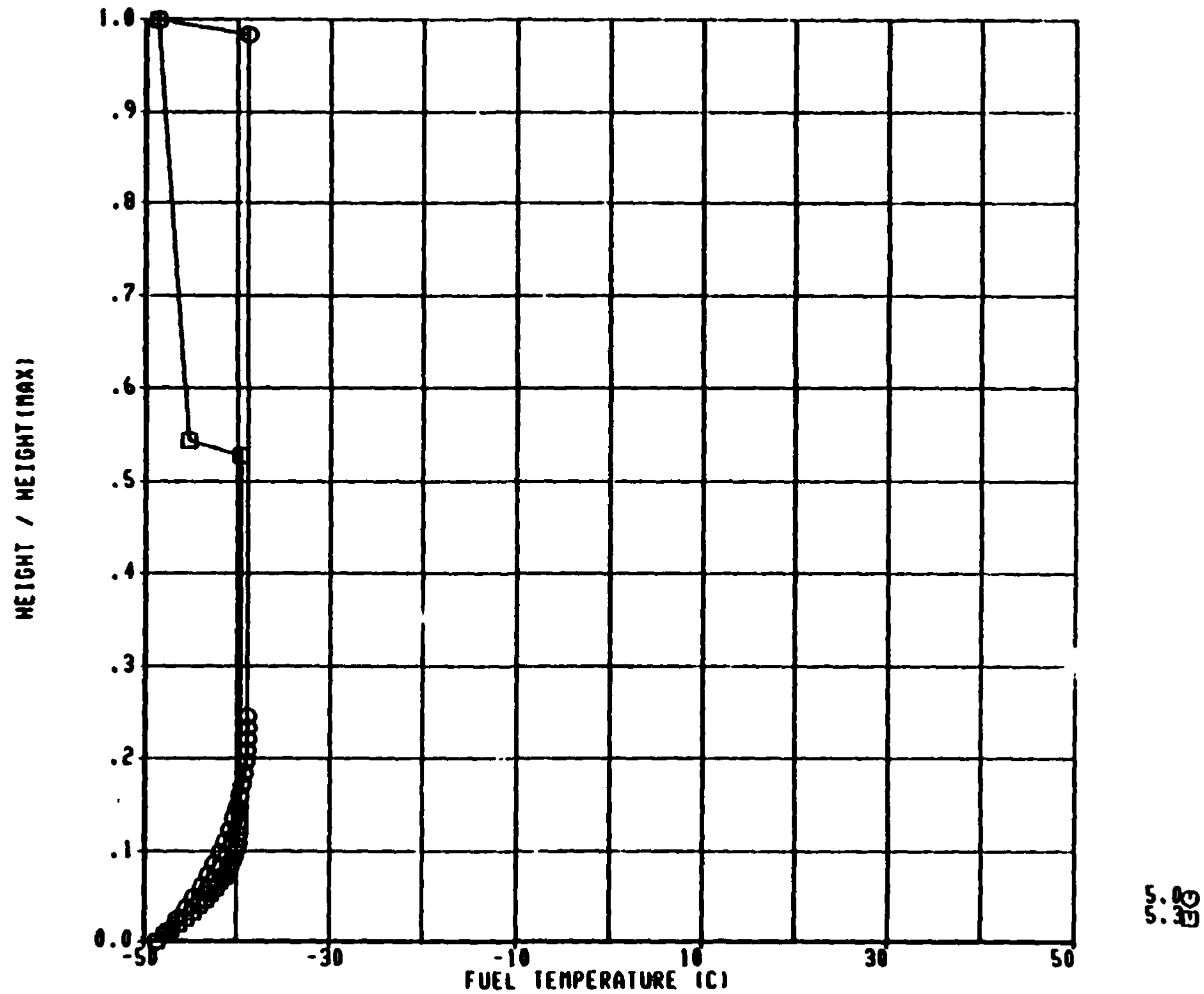


Figure D-2b. Predicted Thermal Profiles KC-135, Track 6

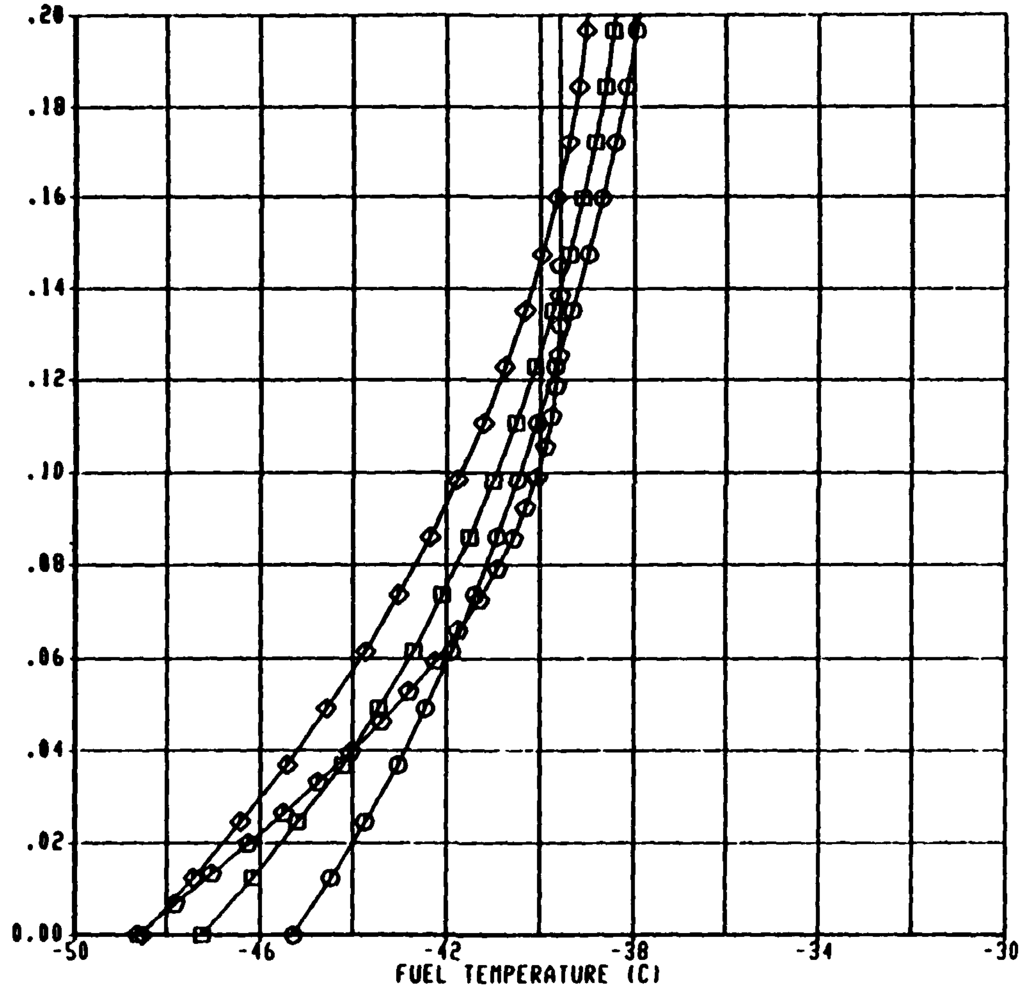


Figure D-2c. Predicted Thermal Profiles KC-135, Track 6

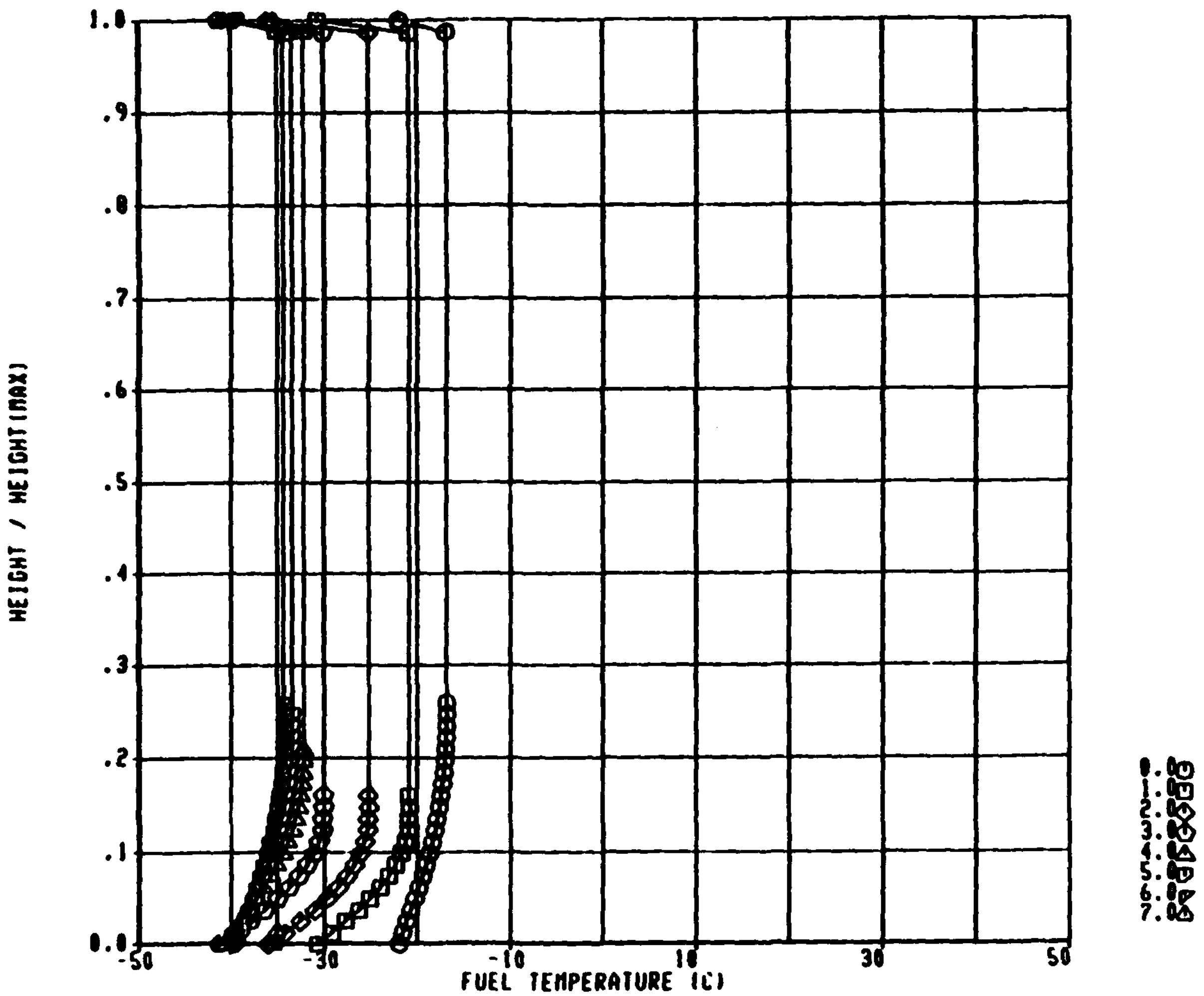


Figure D-3a. Predicted Thermal Profiles B-52, Track 6

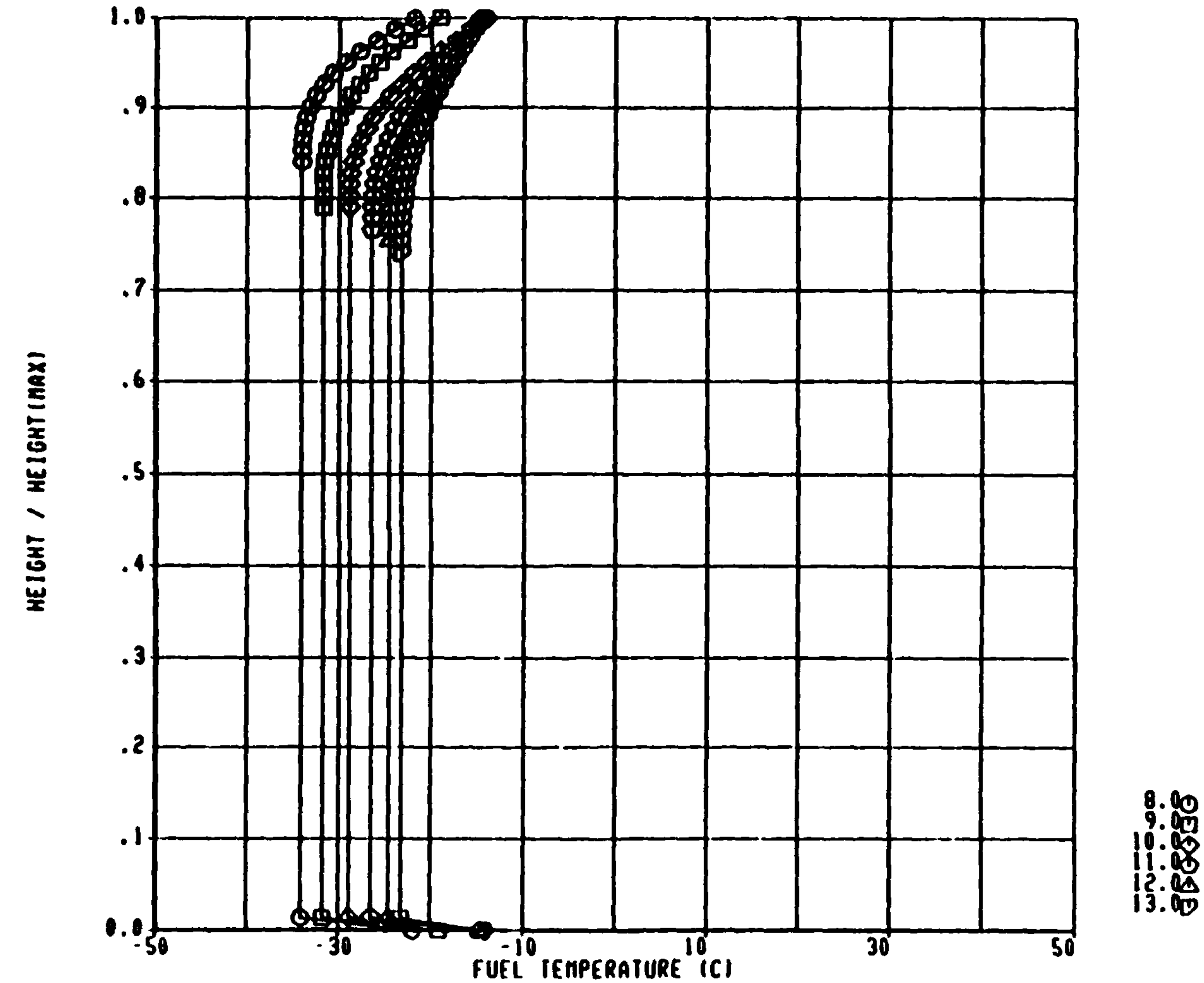


Figure D-3b. Predicted Thermal Profiles B-52, Track 6

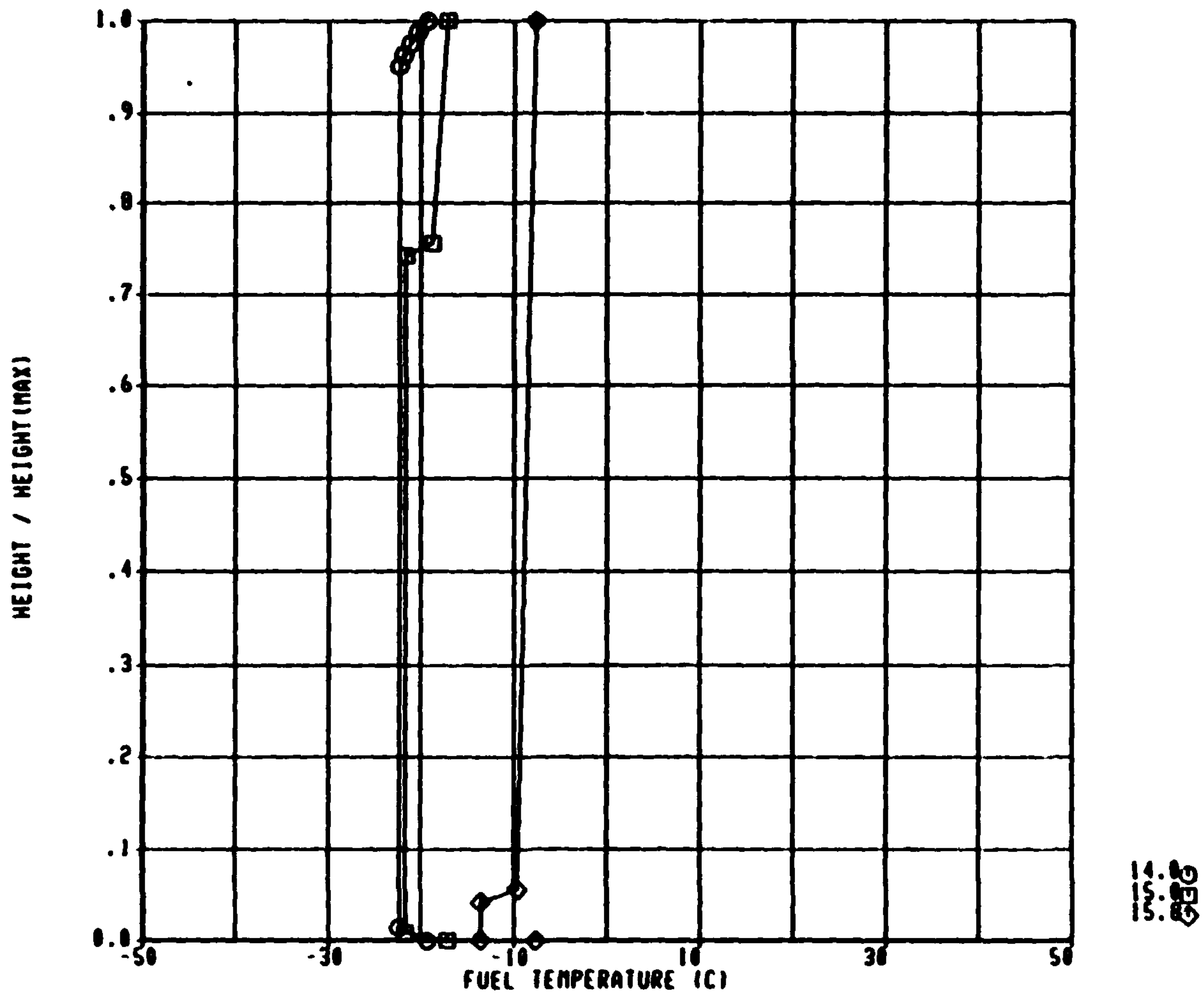


Figure D-3c. Predicted Thermal Profiles B-52, Track 6

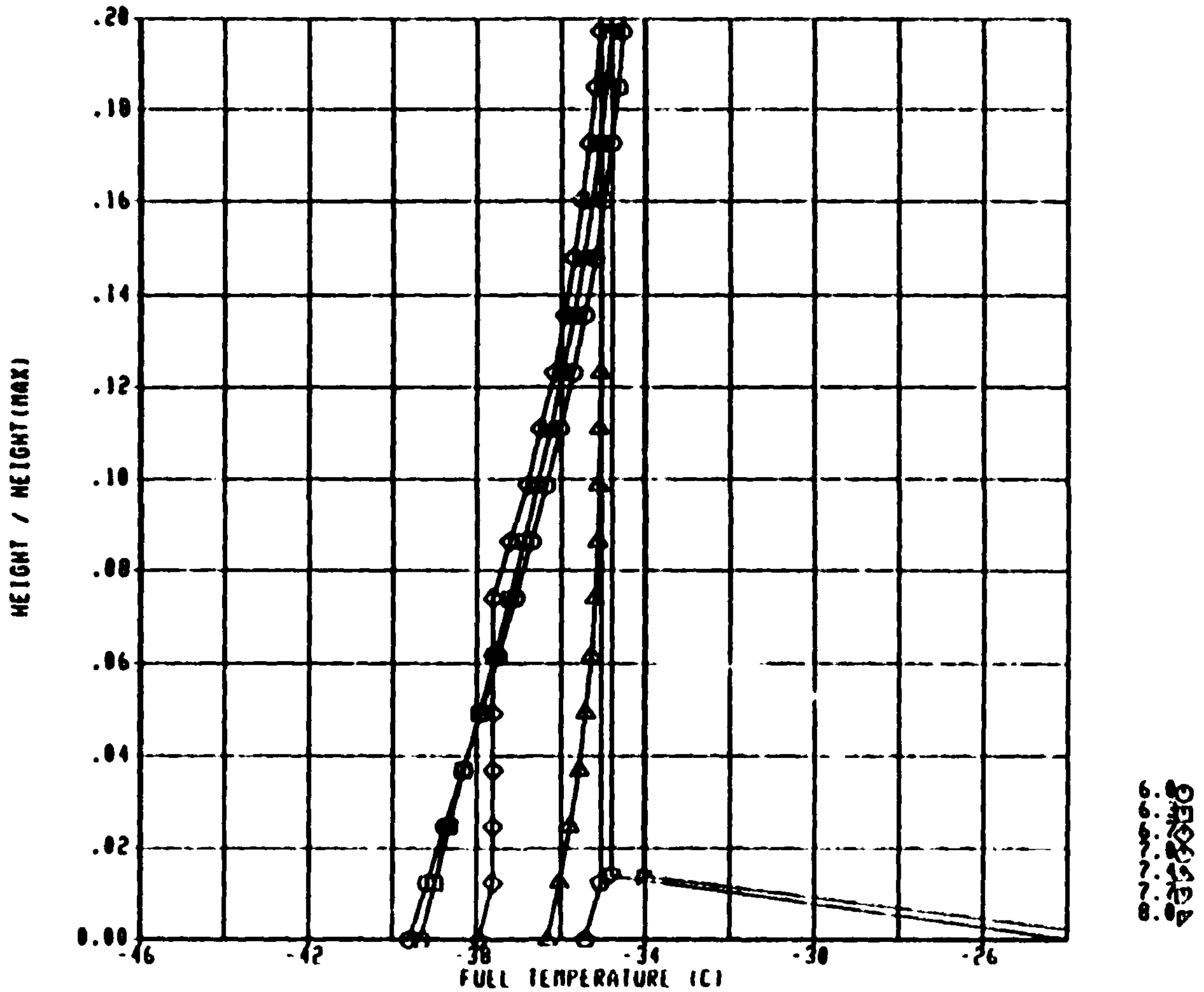


Figure D-3d. Predicted Thermal Profiels B-52, Track 6

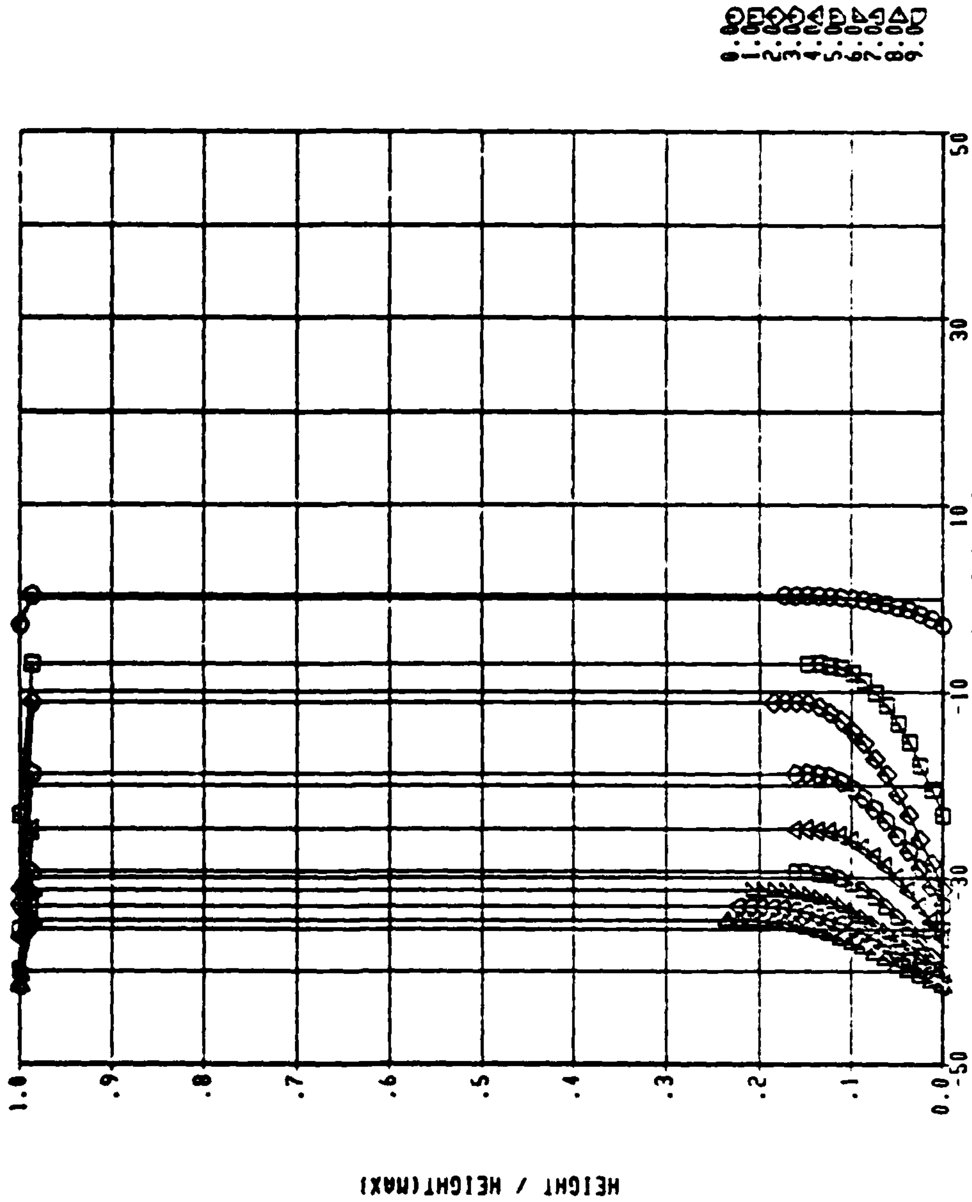


Figure D-4a. Predicted Thermal Profiles B-52, Track 10

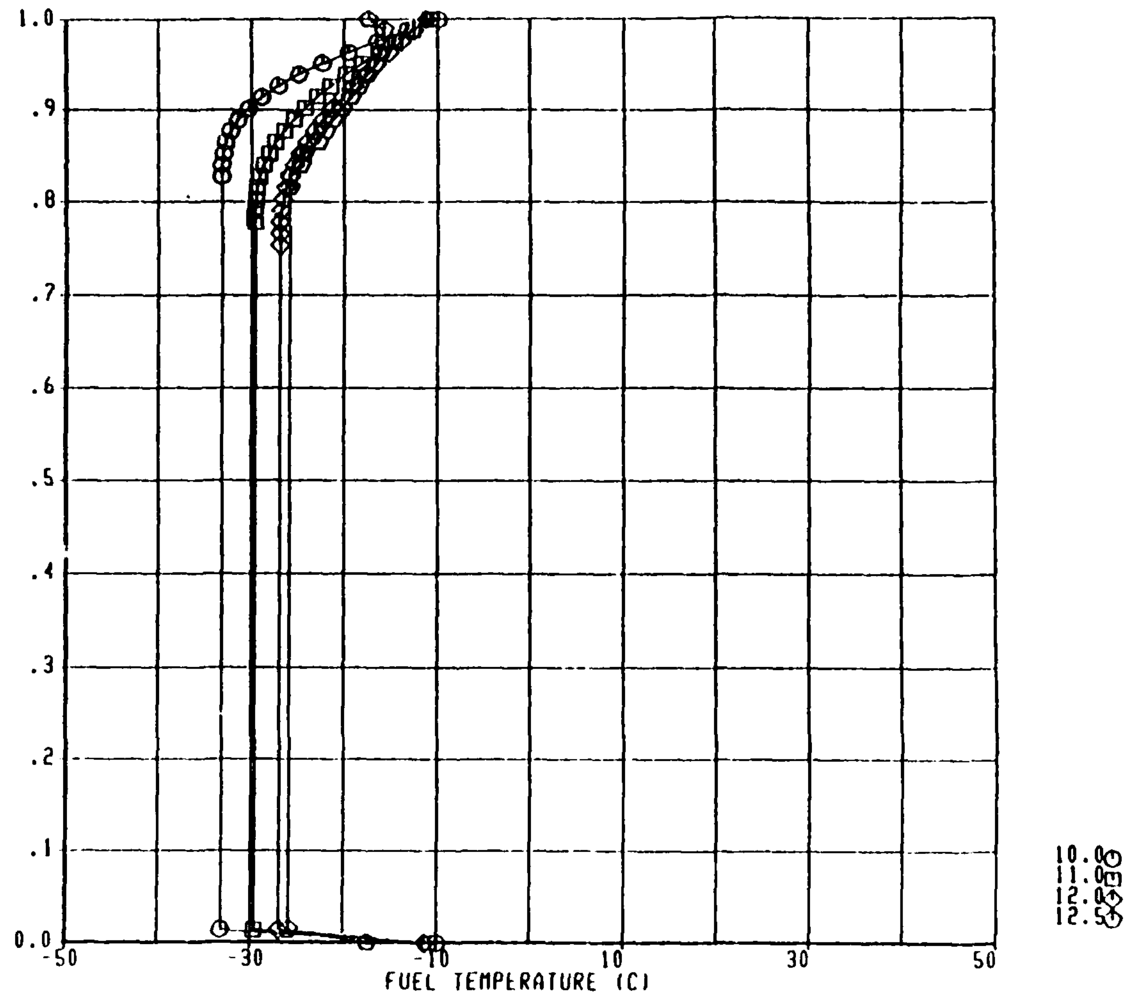


Figure D-4b. Predicted Thermal Profiles B-52, Track 10

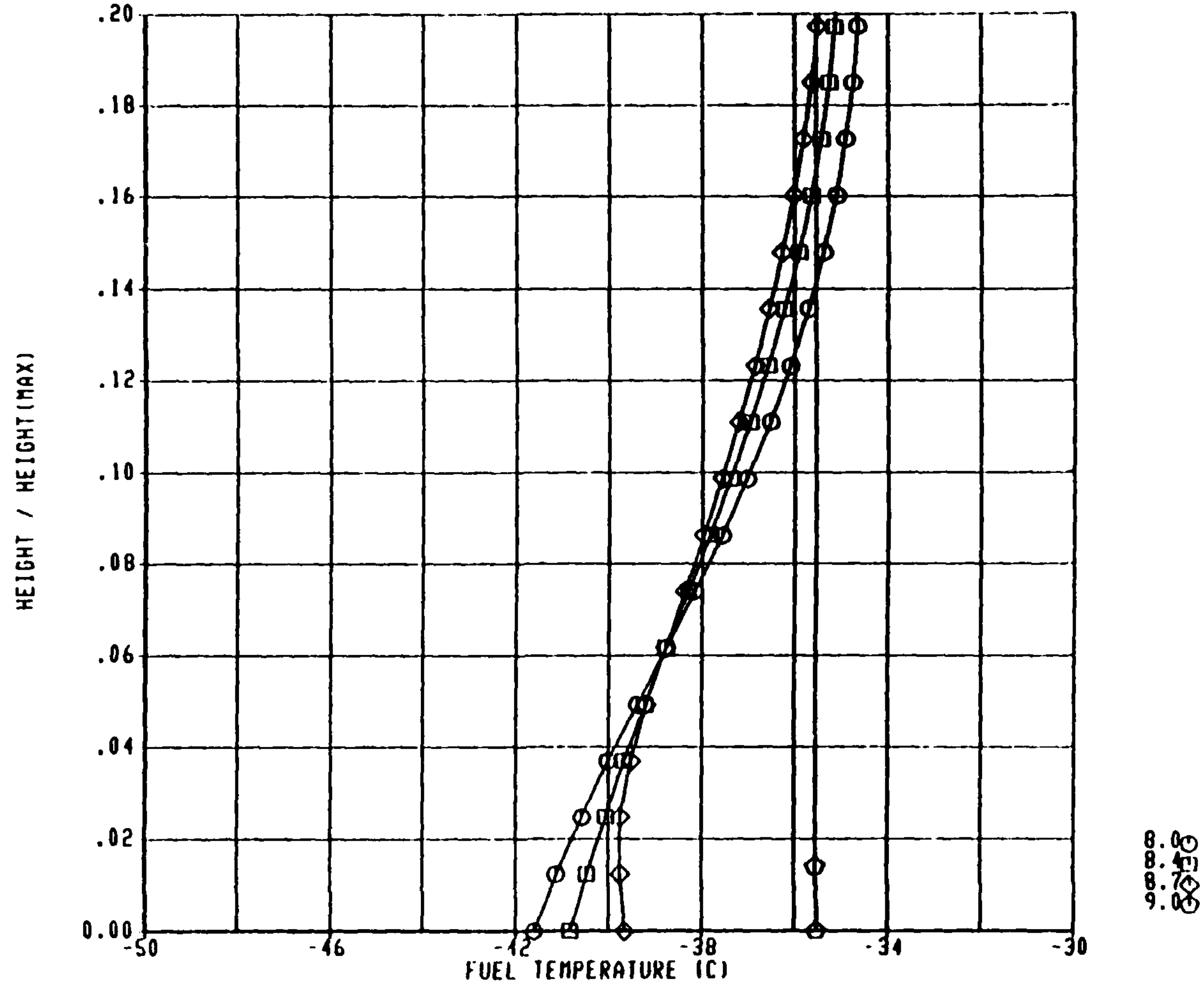


Figure D-4c. Predicted Thermal Profiles B-52, Track 10